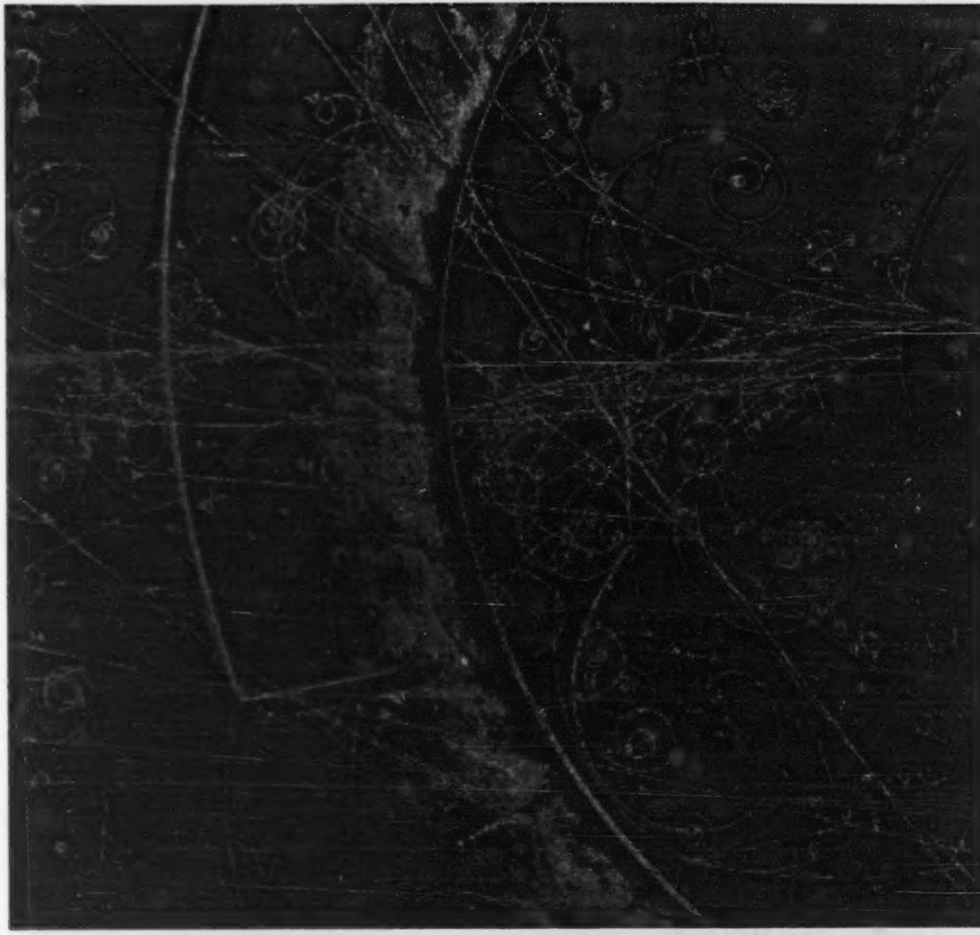

Perspectives on Subatomic Physics in Canada 2006-2016

REPORT OF THE NSERC
LONG-RANGE
PLANNING COMMITTEE

Cover photo:
A colourized image of a particle interaction in a bubble chamber. Although bubble chambers are no longer state-of-the-art detectors, physicists still seek to visualize particle interactions.

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Ce rapport est également disponible en français.

Contents

1 Executive Summary

Subatomic physics is the study of the most fundamental constituents of matter – of everything we see around us. The curiosity that drives this field of research is the same as that felt by any schoolchild with a magnifying glass: What are things made up of? How are they held together? How do they work? Where do they come from?

Today that study has led us to a very detailed, but still incomplete, understanding of the constituents that make up ourselves and the world around us. We understand their behaviour down to a scale of about 10^{-18} meters, and that investigations at that length scale are relevant to conditions in the Universe just a fraction of a second after the Big Bang. The refinement of that understanding is the focus of a coordinated world-wide effort that will lead to dramatic breakthroughs in our understanding of nature – comparable in importance to the revolutions of relativity and quantum mechanics – in the next decade. Canadian science has played a key role in that effort, and is poised to continue.

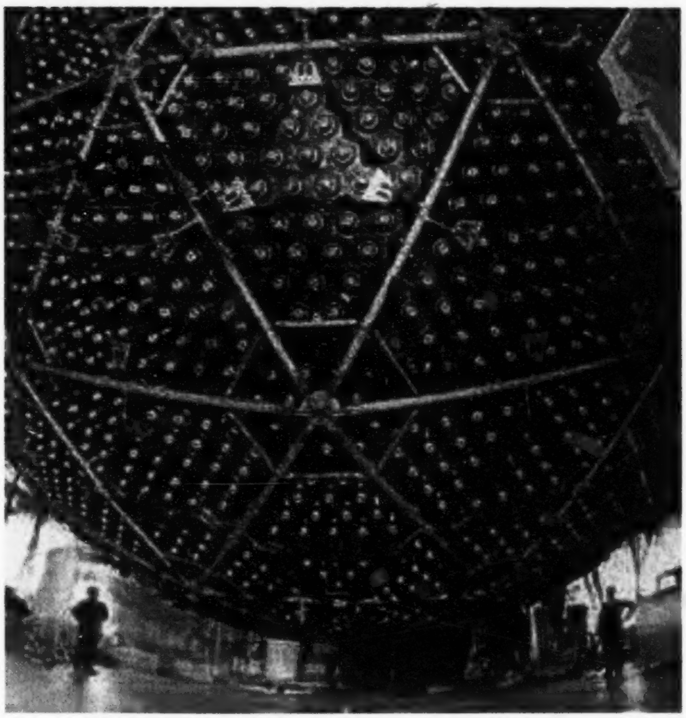
Subatomic physics is a global scientific endeavour. The large capital investments for the accelerators and detectors necessary to make progress in the field require international partnerships in which Canada is a major player. We develop and manage our own forefront facilities that attract foreign scientists, and we are valued contributors to foreign projects.

The global nature of subatomic physics requires a global effort at forward planning and prioritization. In Canada that planning takes the form of five-year plans under the aegis of the Natural Sciences and Engineering Research Council (NSERC). The subatomic physics (SAP) community has carried out several long-range planning exercises since the mid-1990's to identify our highest priority projects, both abroad and in Canada. This report presents the most recent long range plan (LRP), for the period 2006-2011, as well as an examination of the period 2011-2016.

The previous five-year plan, dating from 2001, identified three highest-priority projects as the focus of Canadian subatomic physics: the ATLAS experiment, studying proton-proton collisions at the highest energies available on earth; the ISAC accelerator complex at the TRIUMF lab in Vancouver, studying short-lived radioactive isotopes; and the SNO experiment in Sudbury, studying neutrinos emitted from the Sun.

Over the last five years the Canadian community has delivered on its commitments to these three projects:

- The ISAC exotic ion beam facility at TRIUMF is operational and ISAC-II is under construction. They are the most advanced and highest-intensity radioactive beam facilities in the world. Early studies have resolved a long-standing problem concerning the production rate of ^{22}Na in explosive astrophysics environments, and many more measurements are in progress.



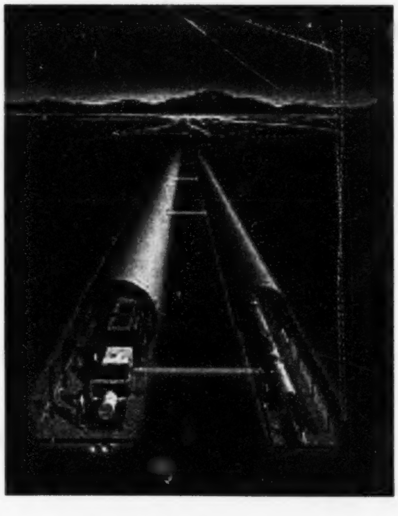
The SNO detector before the cavern, nearly 2 km underground near Sudbury, was filled with water. The SNO experiment's results are one of the major scientific advances in the last ten years, and are a major success of Canadian subatomic physics.

- The ATLAS experiment at the Large Hadron Collider is under construction and will see its first physics events in 2007. The construction of the Canadian contributions to both the detector and the accelerator complex has been completed on time and on budget. Canadian scientists are playing leading roles in the installation of the detector and the development of the data analysis.
- The SNO experiment has unequivocally solved the solar neutrino puzzle by demonstrating that the total neutrino flux from the Sun is consistent with solar models, but that 2/3 of these neutrinos change their identity during their travel to the Earth.

These accomplishments have been realized with a combination of NSERC and non-NSERC financial support, and they have superbly positioned the Canadian subatomic physics community at the beginning of the 21st century. That community now seeks to expand on these accomplishments and reap the benefits of this position of strength and unique opportunity.

The LRP Committee, after extensive consultation with the subatomic physics community, finds that the highest priority projects for the period of this plan should be:

- Full exploitation of the ATLAS experiment at the Large Hadron Collider, exploring proton-proton collisions at the highest energies available;
- Full exploitation of the high intensity radioactive beams for nuclear physics and nuclear astrophysics at ISAC and ISAC-II;
- Completion and full exploitation of the SNOLab facility, the world's best deep underground laboratory, including capital funding for major participation in experiments to be performed at the new facility;
- Participation in a long-baseline neutrino program, and in particular, in the T2K experiment at the Japanese J-PARC facility for the first five years of this plan;
- Vigorous R&D towards participation in the International Linear Collider (ILC), with capital funding for major participation in the 2011-2016 time frame.



An artist's conception of the future International Linear Collider, which will collide electrons and positrons at an energy of approximately 500 GeV and will start operations in the next decade.

In addition, the LRP Committee recommends that a broad program of smaller efforts be maintained to provide breadth and diversity to the Canadian subatomic physics community, and to allow for novel and emerging initiatives.

A strong experimental effort must be complemented by theoretical work. Theory plays a crucial role in subatomic physics by suggesting new directions for experimental studies, interpreting new experimental results, and coalescing these results together with theoretical ideas into a deeper understanding of nature. The Canadian theory community's strength and diversity should be maintained.

This scientific program is intellectually challenging and scientifically compelling by any international standards. It is focused on the most critical scientific questions in the field. The Canadian-based projects in the program (SNOLab and ISAC) are the world's best facilities of their type, and have strong Canadian leadership.

Thanks to recent reinvigoration through faculty renewal and capital investments from outside of NSERC, the Canadian subatomic physics community is superbly placed to carry out this program. Unfortunately, its ability to do so is not assured. There is an urgent need to increase operating funds to exploit the opportunities created by the capital investments.

Over the last several years, non-NSERC sources have injected approximately $75M of new capital funding into subatomic physics. A general rule of thumb is that total life-time operating support for major facilities is approximately equal to their capital costs. However, the annual funds provided by NSERC to subatomic physics have only increased over the last five years by approximately $1M. The LRP Committee identified this as the single biggest risk facing the field today: without new operating funds sufficient to enable the dynamic and growing Canadian subatomic physics community to exploit the recent capital investments, we will lose our position of strength and these infrastructure investments will fail to live up to their potential.

The committee specifically recommends:

- an urgent solution to the immediate problem posed by the lack of operating funds for the new CFI-funded SNOLab facility;

- doubling the annual NSERC subatomic physics envelope from $23M to $46M over a period of ten years, providing $100M in new subatomic physics funding over that time.

Finally, in view of the central role played by the TRIUMF laboratory in Canadian subatomic physics, and the importance of University-based technical infrastructure to the community, the committee makes the two following policy recommendations:

- The central role of the TRIUMF lab in providing infrastructure and support to subatomic physics in Canada must be nurtured and strengthened, with particular attention to the transparency of the federal budget process and how the budget reflects TRIUMF's mandate and five-year plan. In support of its mission, TRIUMF should be able to access all SAP-relevant funding agencies, including the CFI.

- The NSERC infrastructure guidelines must be examined closely to ensure that subatomic physics infrastructure will continue to be eligible for funding; that infrastructure must be managed in a way that guarantees open access to the broad Canadian SAP community.

The next five to ten years will be extremely exciting for Canadian subatomic physics. We are strong players in all our top priorities, which address globally important science questions. The LRP Committee is confident that this potential can be realized with a coherent strategy on the part of granting agencies and governments to provide funds at a level substantially above the current NSERC support and more commensurate with the total level of recent support.

Reader's Guide

The structure of this report is as follows.

Section 2 summarizes the overarching scientific questions in subatomic physics.

Section 3 explains the context – both Canadian and global – in which this science is carried out, describes the Canadian subatomic phyics community, including its demographics and recent successes, and outlines the LRP Committee's vision for the community's evolution over the lifetime of this plan.

Section 4 gives a **more technical description of the main research topics** in the Canadian subatomic physics community today.

Section 5 addresses the economic impact of subatomic physics in Canada, with particular attention to the training of highly qualified personnel.

Section 6 explains the **complexity of subatomic physics funding and support** through a discussion of the many different agencies and institutions that participate in subatomic physics in Canada.

Section 7 addresses in detail the NSERC funding scenarios that the long-range planning committee was asked to address.

Section 8 contains the conclusions, including the detailed recommendations of the committee.

Together, *sections 2, 3, 5,* and *8* provide a **non-technical overview** of this document concentrating on the science questions.

Finally, *Section 9* contains supplementary material including a glossary of terms and acronyms.

2
The Fundamental Questions of Subatomic Physics

We live in fascinating times. Recent discoveries indicate that roughly 95% of the Universe consists of matter and energy in forms completely unknown to us, and theoretical advances predict a whole new world of particles that should be discovered at the next step towards the energy frontier. Scientists are close to making major breakthroughs that will revolutionize our understanding of the Universe and its constituents. As a consequence, numerous international studies have been commissioned to determine the most urgent questions in subatomic physics today. The central issues that appear repeatedly in these studies are:

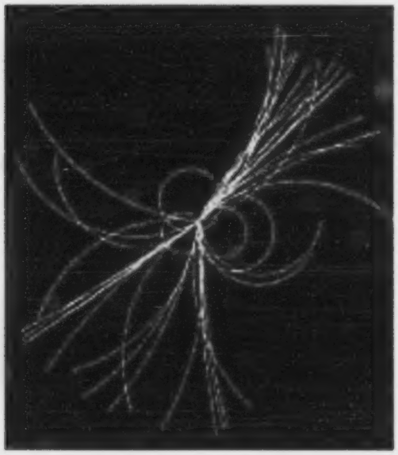
- What is the nature of new particles and physics beyond the Standard Model? Can a unified theory encompassing gravity and particles be developed?
- How do particles acquire mass? Does the Higgs particle exist and generate masses, or is new physics required?
- What is the nature of the dark matter and dark energy that comprise 95% of the Universe?
- What was the origin of the Universe? How is it evolving and what caused the asymmetry that led to a Universe dominated by matter rather than antimatter?
- What are the masses of neutrinos, and how have these particles shaped the evolution of the Universe?
- Can the theory of quark and gluon confinement quantitatively describe the detailed properties of hadrons?
- What mechanisms are responsible for the synthesis of heavy elements?

Canadian subatomic physics is making great progress in addressing these profound questions, on both experimental and theoretical fronts. This research requires highly advanced equipment and facilities and a concerted effort at an international level, including collaboration between nuclear and particle physics, astroparticle physics, cosmology, and astronomy.

2.1 Addressing the Fundamental Questions

Answering these fundamental questions will require the observation and theoretical understanding of new physics processes. Research facilities around the world will probe this new physics in a variety of ways, each addressing several aspects of the fundamental questions listed above. New high energy accelerators like the Large Hadron Collider at CERN and the future International Linear Collider are expected to discover new heavy particles at the "high energy frontier". In contrast, understanding the subtleties of rare processes in detail is the raison d'être of experiments at the "precision frontier". A major advance in probing nuclear physics processes is the development of radioactive beam facilities like ISAC at TRIUMF. Here "designer beams" provide a new window of opportunity as a wide range of neutron- or proton-rich isotopes can be created, accelerated and studied. A common feature of astroparticle physics searches is the need to detect very rare interactions in a competing background from natural radioactivity and cosmic rays. For this reason, the detectors must have ultra-low radioactivity levels and be shielded deep underground in a clean facility like SNOLab in Sudbury. Finally, a close coupling between theory and experiment is essential to address these fundamental questions.

In the following sections we address different facets of the exploration of the fundamental questions listed above. In many cases, several of the questions are addressed or touched upon by a single approach.



A simulation of particles emerging from the decay of a Higgs particle produced in a high-energy electron-positron interaction.

A whimsical view of new ideas in theoretical particle physics.

The Standard Model: What new physics lies beyond?

The current theory of subatomic physics is known as the "Standard Model". It was emphatically confirmed in 1983 with the discovery of two new particles, the *W* and *Z* bosons, whose masses and other properties were precisely as predicted by the model. In the ensuing decades, the Standard Model has been subjected to intense scrutiny and no significant discrepancies have emerged; it has been extraordinarily successful in describing the subatomic world in a fully self-consistent mathematical theory.

However, the Standard Model contains many apparently arbitrary physical parameters. The observation of neutrino oscillations by the Sudbury Neutrino Observatory (SNO) indicates non-zero neutrino masses that are much smaller than the other particles, possibly hinting at physics beyond the Standard Model. In addition, there is mounting evidence that dark matter is formed of particles not found in the Standard Model. Hence, it is anticipated that nature is represented by a more general "beyond the Standard Model" theory which overcomes the Standard Model's shortcomings.

In the Standard Model, the *W* and *Z* particles acquire mass through a process of symmetry breaking. The simplest implementation of this symmetry breaking requires the existence of a currently unobserved particle called the Higgs boson. The data obtained to date favour a low mass Higgs which should be observable at the Large Hadron Collider (LHC). However, there are theoretical inconsistencies in this simplest of descriptions of mass generation and if a light Higgs is observed it is expected to be part of a more complete theory such as supersymmetry. If supersymmetry exists, many additional particles should be discovered by the LHC. If the Higgs is not observed, some other mechanism beyond the physics of the Standard Model must be responsible for symmetry breaking, which would also lead to new dynamics at energies accessible to the LHC. Either case is expected to reveal new physics beyond the Standard Model. Understanding the mechanism responsible for the origin of mass, and revealing new physics beyond the Standard Model, are the principal objectives of the experimental program at the LHC.

Nuclear physics experiments at low and intermediate energies also have a role to play in the search for physics beyond the Standard Model. Carefully selected nuclei provide a "quantum laboratory" for very high precision measurements of Standard Model observables, and for searches for phenomena forbidden or suppressed by the Standard Model. For example, the matter/antimatter asymmetry in the Universe may be explainable in terms of time reversal asymmetry, which may be observed by experiments at ISAC probing specially selected nuclear systems.

There is also a tremendous theoretical effort to formulate new theories describing the nature of physics beyond the Standard Model. These include supersymmetry, models with extra space-time dimensions, and string theories. The latter are particularly interesting in terms of a unified general theory as they incorporate quantum gravity with elements of the Standard Model.

Dark matter: What is the principal component of mass in the Universe?

Increasingly precise data on the non-uniformity of radiation produced in the early Universe (the Cosmic Microwave Background), velocity profiles of rotating galaxies, and observations of distant supernovae have given us very detailed information about the composition and mass of the Universe. These results have led to the startling realization that roughly 95% of the energy content of the Universe is completely unknown. Current measurements reveal that roughly 25% of this energy content is comprised of non-luminous "dark matter", predominantly contained in large halos surrounding galaxies. The matter we see (stars, planets, etc.) accounts for only about 1%, and the interstellar gasses account for approximately 4%. The remaining 70% appears to be in the form of dark energy, which behaves like a repulsive gravitational force, driving the expansion of the Universe at an ever increasing rate.

Some progress has already been made on the nature of dark matter. It is now widely believed that it is composed of weakly interacting massive particles (WIMPs) drifting slowly through the galaxy. The Earth passes through this WIMP wind and there is a realistic hope that experimental initiatives currently under development will observe dark matter in the coming years.

As mentioned above, supersymmetric theories predict the existence of many new particles which may be observable at the LHC. One of the consequences of these theories is that they naturally contain a lightest super-symmetric particle. If stable, this particle could well account for the missing dark matter of the Universe. It is very appealing that a dark matter candidate arises naturally from general theoretical developments in subatomic physics, and does not require an *ad hoc* theory to explain its existence.

The search for dark matter is a prime example of a synergy within subatomic physics. Numerous experimental programs are underway to detect dark matter directly, but they will not be in a position to comment on the supersymmetric nature of the particles they observe. On the other hand, if supersymmetric particles exist, they should be observable at the LHC, where measurements of

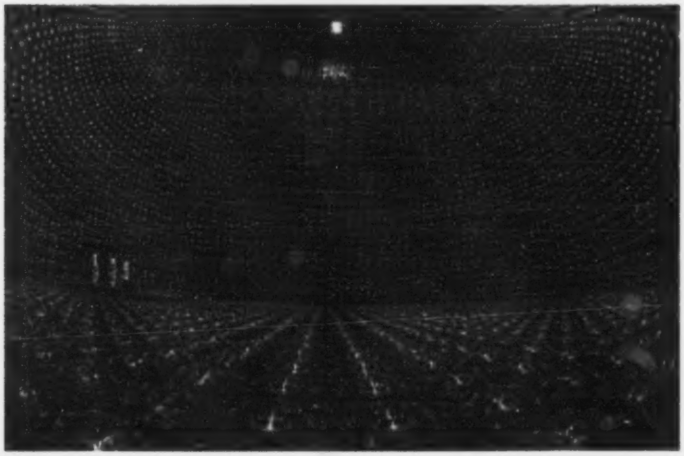
their production and decay modes will identify them as supersymmetric in nature. Even so, these accelerator searches will not be able to identify such particles as being dark matter. Thus, both types of searches will be necessary to conclusively show that dark matter is supersymmetric.

Dark matter may also be observed indirectly. WIMPs that scatter in massive bodies like the Earth or Sun may become gravitationally bound at the centre of these objects, where they would be sufficiently numerous that their annihilation would lead to a flux of high energy gamma rays or neutrinos observable by terrestrial instruments. Input from all of these programs – direct dark matter searches, new accelerators, and dark matter annihilation searches – will help to elucidate the nature of dark matter and supersymmetry. Their detection would be a breakthrough of monumental proportions.

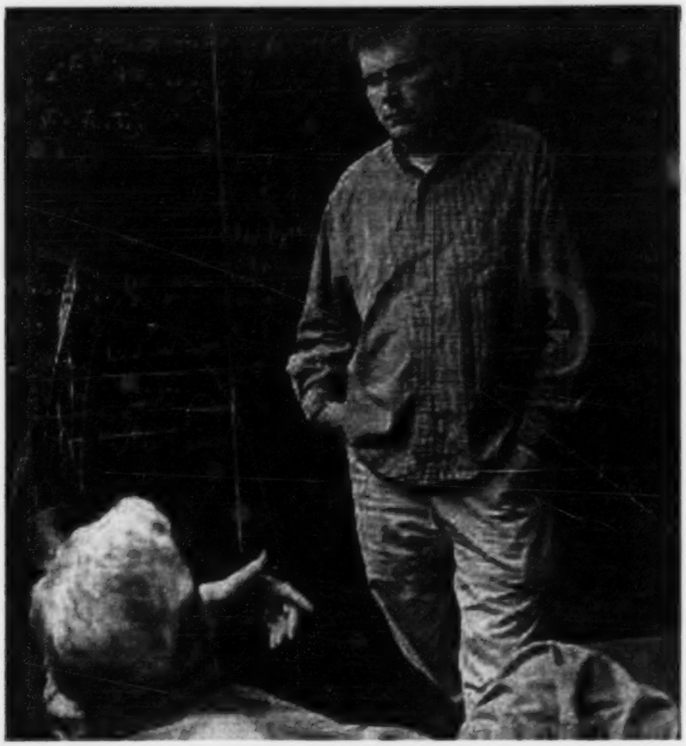
The elusive neutrino: How has it shaped the structure and evolution of the Universe?

The discovery of neutrino oscillations by SNO and the Japanese Super-Kamiokande experiment implies that neutrinos are massive – that is, that they have a small, but non-zero mass. This has far reaching consequences for the roles that neutrinos may play in the structure and formation of the Universe.

One possibility is that massive neutrinos may be related to the matter/antimatter asymmetry observed in the Universe. We live in a matter-dominated Universe. How this came to be is one of the most fundamental of questions, and may be explained by the violation of a symmetry in nature known as CP, describing how physics laws should be invariant under the exchange of Charge Conjugation (C – exchanging particles and antiparticles) and Parity (P – exchanging spatial coordinates) transformations.



The SuperKamiokande neutrino detector in Japan. Together, SuperK and SNO results have had far-reaching consequences for our understanding of the behavior of neutrinos.



Theoretical physicists at the Perimeter Institute in Waterloo, Ontario.

CP violation as measured in the quark sector is very small and is insufficient to account for the observed matter/antimatter asymmetry. CP violation in the neutrino sector has yet to be measured, but could ultimately be responsible for the observed asymmetry. An understanding of this phenomenon via a long-baseline neutrino oscillation program is therefore essential to an understanding of the early Universe and the presence of matter in it.

Understanding the origin of neutrino masses and whether the neutrino is its own antiparticle (called a Majorana neutrino), is fundamentally important. Majorana neutrinos are preferred in most theories because the mechanism that produces neutrino masses is then quite natural and could be associated with a large CP violating phase. Neutrinoless double beta decay experiments are essential to measure the absolute masses of neutrinos, determine if they are Majorana particles, and hence conclude whether CP violation in the neutrino sector is a real possibility. A knowledge of neutrino masses also helps to understand their gravitational influence on large-scale structure formation and evolution in the early Universe.

SNO has unequivocally demonstrated that solar neutrinos oscillate. These oscillations are widely believed to be driven by interactions with matter in the Sun. However, SNO cannot determine the exact mechanism by which oscillations occur, and other mechanisms, including new physics with non-standard neutrino interactions or mass varying neutrinos, have been proposed. Solar neutrino studies at low energies will be able to probe the origin of these oscillations.

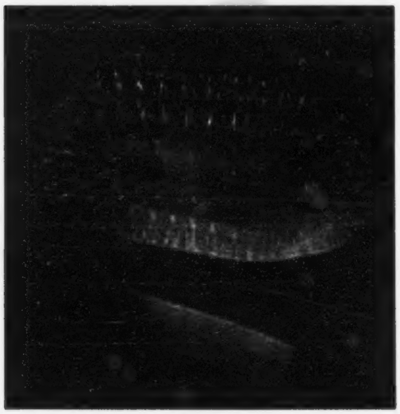
The neutrino is also an excellent probe of other astrophysical processes. In contrast to gamma rays, which can take millions of years to scatter from the core of the Sun to its surface, neutrinos arrive directly at the Sun's surface and therefore carry information about the nuclear processes occurring in the core. Similarly, neutrino production also reveals processes occurring in supernovae and other high-energy environments.

The world of quarks and gluons: How does confinement lead to the basic states of matter?

In the Standard Model, the interactions between quarks (which have mass) and gluons (which are massless) are described by a theory called Quantum Chromodynamics (QCD). Quarks and gluons combine to form the familiar protons and neutrons as well as other hadrons, but the details of QCD remain poorly understood.

To illustrate why the solution of this problem is important, consider the mass of regular matter. The mass of atoms is concentrated in their nuclei; the surrounding electrons are crucial for determining how atoms interact with each other, but they provide less than a part in a thousand of the mass. The nuclei are assembled from protons and neutrons which in turn are made from quarks and gluons. Thus, most of the mass of matter can ultimately be traced back to the quarks and gluons described by QCD. However, a realistic estimate of the contribution of the quark masses to the mass of the nucleus is small: just a few per cent of the total proton mass. Hence, 95% of the proton (or neutron) mass, and thus 95% of the mass of ordinary matter, emerges from the interactions of quarks with massless gluons. There is, as yet, no detailed explanation for this phenomenon.

While QCD is now firmly established as the fundamental theory of the strong interactions between quarks and gluons, our understanding is lacking on several critical fronts. In short distance (high energy) interactions, the interaction is relatively feeble, so mathematical methods can be used to solve a subset of the theory. In contrast, in lower-energy (long distance) interactions, quarks and gluons are found to interact with one another exceedingly strongly, leading to their confinement to form the building blocks of conventional matter: protons and neutrons. Quantitative QCD calculations in this regime remain one of the greatest intellectual challenges in physics.



Visual representation of the energy storage within a heavy meson as obtained from numerical simulations (lattice QCD). The structure between the quark-antiquark pair is a colour "flux tube" of the gluonic field. Advances in lattice QCD techniques make increasingly detailed visualizations possible.

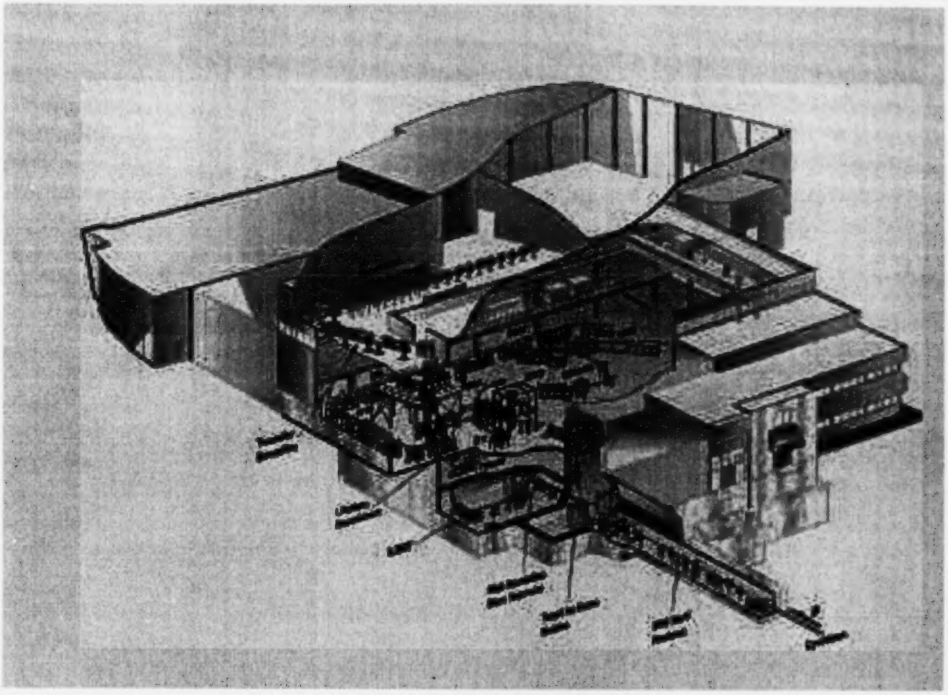
This challenge is now being taken up. The modeling techniques of former decades have recently been replaced by rigorous theoretical methods, and the international community is developing some of the largest computing facilities on the planet, dedicated exclusively to the numerical solution of QCD problems. This, in combination with advances in effective field theories and precision data from experiments, is expected to revolutionize the field. Progress is being made toward the detailed understanding of the structure of protons, neutrons, and other hadrons. Furthermore, QCD predicts exotic states of matter, such as hybrids and glueballs, that have never been unambiguously observed. Experimental searches for such exotics are expected to be implemented within the timeframe of this long range plan; their discovery may verify the accuracy of QCD as a description of the real world.

Nuclear Structure and Nuclear Astrophysics: How and where are the heavy elements produced?

The nucleus contains over 99.9% of the mass of the atom and, hence, of ordinary matter in the Universe. It is a complex quantum mechanical many-body system, and understanding it is of fundamental importance if we are to understand how the Universe evolved and how the elements are produced.

Nuclear physics has made tremendous progress in recent years due to facilities that allow the production of isotopes with specific neutron-to-proton ratios, which permit investigation of the inner workings of these complex many-body systems. This controlled rearranging of the constituents of nuclei has led to the discovery of new forms of nuclear matter, and has also provided access to nuclei which play key roles in the formation of the elements in the Universe. In general, studies of nuclear structure and nuclear astrophysics aim to elucidate the origin, composition, structure, and evolution of atomic nuclei, and their role in astrophysical systems. The development of a unified theory of the atomic nucleus, with predictive power for both the structures of undiscovered nuclei and the role of these nuclei in astrophysical processes, is the long-range scientific goal of the international nuclear structure and nuclear astrophysics communities.

The properties of atomic nuclei are essential in determining the structure and evolution of the cosmos. Only the lightest elements (hydrogen, helium, and lithium) were created in the Big Bang; all of the heavier elements have been synthesized through nuclear reactions in normal stars, novae, X-ray bursts, supernovae and other astrophysical environments. The reactions in the synthesis of the elements involve many unstable exotic nuclei that exist only under the extremes of temperature and pressure found in stars and supernovae. With the advent of radioactive beam facilities, such as ISAC, it is now possible to produce



Schematic of the ISAC-I (foreground) and ISAC-II (background) radioactive ion beam complex at TRIUMF in Vancouver, British Columbia. The proton beam from TRIUMF's main cyclotron enters at lower right.

these nuclei in the laboratory and study their evolution and synthesis in a controlled way. Determining the properties of these nuclei is essential to our understanding of the timescales and energy releases involved in the explosive astrophysical events that produce the elements and then subsequently eject them as the ashes that eventually condense to form new stars and planets, including Earth and all life on it.

In summary, the LRP Committee is confident that exciting and fundamental discoveries will be made during the period covered by this long-range planning exercise. It is possible that these discoveries will transform our understanding of the origin of matter and energy and the ongoing evolution of the Universe. Canada is poised to be a world leader in this field with active leadership and participation in the most critical research. The synergies between both theoretical and experimental nuclear physics, particle physics, and astrophysics found in Canada create a healthy and balanced approach to subatomic research. With continued strong support, Canada will be a leader in what may be the next renaissance in science.

3
Global Science, Canadian Strength and Vision

The international subatomic physics community has reached a consensus on its most important scientific questions and on the ways to attack them. Canadian scientists and Canadian science have participated in reaching this consensus, and their research is carried out within it. In this section we present that context, give a brief introduction to the Canadian subatomic physics community and its recent successes, and articulate a vision for its future that builds on the community's strengths, capabilities, and achievements.

3.1 The Context of Subatomic Physics

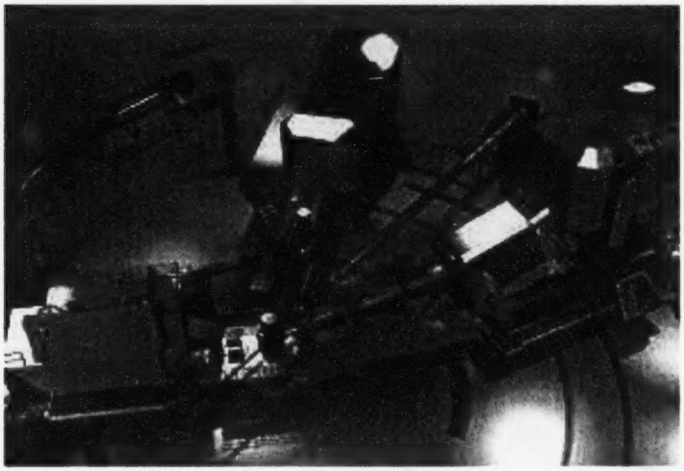
The scale of the machines and the human effort involved in confronting the fundamental questions of subatomic physics makes this a truly global science. No single country can afford to perform all the relevant subatomic physics experiments, and a world-wide network of facilities has grown up which ensures broad coverage and complementary measurements. This international network of laboratories and facilities is at the heart of the global subatomic physics effort. The laboratories provide both accelerators and critical local infrastructure supporting the university-based user community. Canada hosts two such laboratories (TRIUMF and SNOLab) and makes strong contributions to experiments at international labs.

International subatomic physics is a well-coordinated effort. A number of different planning exercises and oversight bodies exist, all driven by the overarching scientific questions of our field, together with the current technological state-of-the-art and prospects for both experimental and theoretical progress. Canadian subatomic physicists work together with our international partners planning and carrying out projects in subatomic physics.

University researchers play a unique and central role in subatomic physics research, even though the experiments tend to be too large to be hosted at any one university. University-based groups propose experiments, design, develop, and build detector components, participate in data-taking, and lead physics analyses. Faculty are the heart of the experimental subatomic physics program, both because they lead experiments and because universities are the core of the recruitment, education and training of students and other highly qualified personnel who are so critical to the success of our science.

Existing Facilities

The **TRIUMF** laboratory in Vancouver, which started operation in 1974, is Canada's national laboratory for particle and nuclear physics. Today, TRIUMF's flagship program is the ISAC radioactive beam facility, the world's leading facility for the production of exotic short-lived isotopes. ISAC's unique capabilities allow critical and challenging measurements which have already made important contributions to our understanding of the nuclear processes driving stars and the mechanism which produces the heavy elements in the Universe. Moreover, the ISAC facility allows unique weak-interaction Standard Model tests and investigations of new forms of nuclear structure. These investigations will continue at ISAC-II, probing the structures of exotic nuclei critical to our understanding of high-energy environments in astrophysics such as novae, supernovae, and gamma-ray bursts.



Schematic drawing of a proposed spectrometer system for the Hall-C area at Jefferson Lab in Virginia. At far right and left are the 7 GeV/c HMS and 1.6 GeV/c SOS magnetic spectrometers; at center is the proposed 12 GeV/c SHMS spectrometer, to be constructed as part of the JLab 12 GeV upgrade.

TRIUMF also plays a significant role as an infrastructure facility for Canadians participating in major international experiments, such as the ATLAS experiment at CERN and the T2K long baseline neutrino experiment in Japan. The expertise that exists at TRIUMF in the areas of accelerator physics and detector R&D have helped Canada make significant "in-kind" contributions to these projects and to the accelerators that enable them.

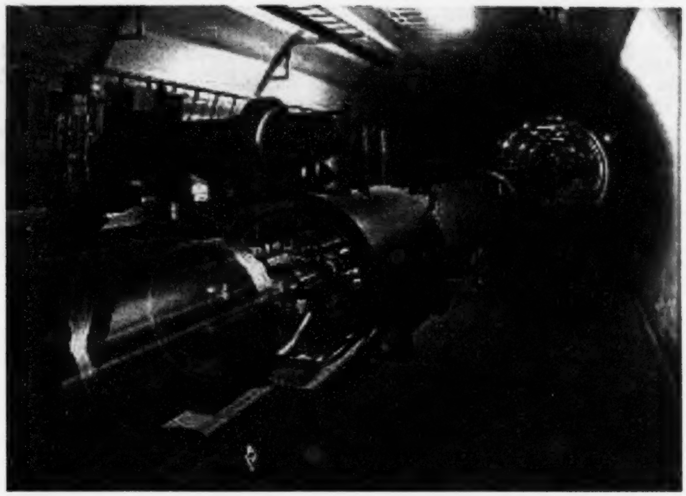
Canada's second major subatomic physics facility, **SNOLab**, is under construction at the Inco Creighton mine in Sudbury, at the same depth as the successful Sudbury Neutrino Observatory experiment. SNOLab will be the deepest underground experimental facility in the world, having the lowest backgrounds from cosmic rays and therefore offering unique sensitivity to rare processes. As one example, SNOLab is the ideal location to host searches for dark matter. Experiments at SNOLab will be capable of making contributions to our understanding of neutrino physics that are comparable to, or greater than, the important discoveries already made by the Sudbury Neutrino Observatory. SNOLab has an international Experiment Advisory Committee that has reviewed a first submission of letters of intent. Nine potential projects have been identified, most of which have strong Canadian participation. Efforts are now underway to complete R&D associated with these projects and to clarify their ability to take full advantage of SNOLab's unique characteristics.

There are many international laboratories that have played important roles in subatomic physics. In the coming decade, Canadian activities will be concentrated at a small number of these labs, which are briefly described below.

The European Laboratory for Nuclear and Particle physics, **CERN** near Geneva, Switzerland, is the preeminent international particle physics laboratory today. CERN hosts the Large Hadron Collider (LHC) which will extend our "energy frontier" by over an order of magnitude, the largest such increase in decades. Canadians have made significant contributions to both the LHC accelerator complex and to the ATLAS detector. ATLAS will be a strong focus of the Canadian, and world-wide, particle physics program over the next decade.

The **Thomas Jefferson National Accelerator Facility (JLab)** in Virginia is part of a network of labs funded by the U.S. Department of Energy. These labs have hosted pivotal experiments over the past half century, including many with large Canadian participation. Today, JLab hosts much of Canada's nuclear physics efforts abroad, and Canadian nuclear physicists play leading roles in a number of key experiments there.

Japan hosts the **J-PARC** laboratory and the **Super-Kamiokande** underground neutrino detector which made pivotal measurements of the oscillations of neutrinos produced by cosmic ray collisions with the atmosphere. The T2K experiment will use a new accelerator neutrino beam from J-PARC directed at the Super-Kamiokande detector to precisely probe the properties of neutrinos, a direct follow-up to the oscillation of neutrinos observed by the Sudbury Neutrino Observatory and Super-Kamiokande.



A mock-up of the LHC tunnel at CERN showing the two beam pipes in which the 7 TeV proton beams will travel around the 27-km ring.

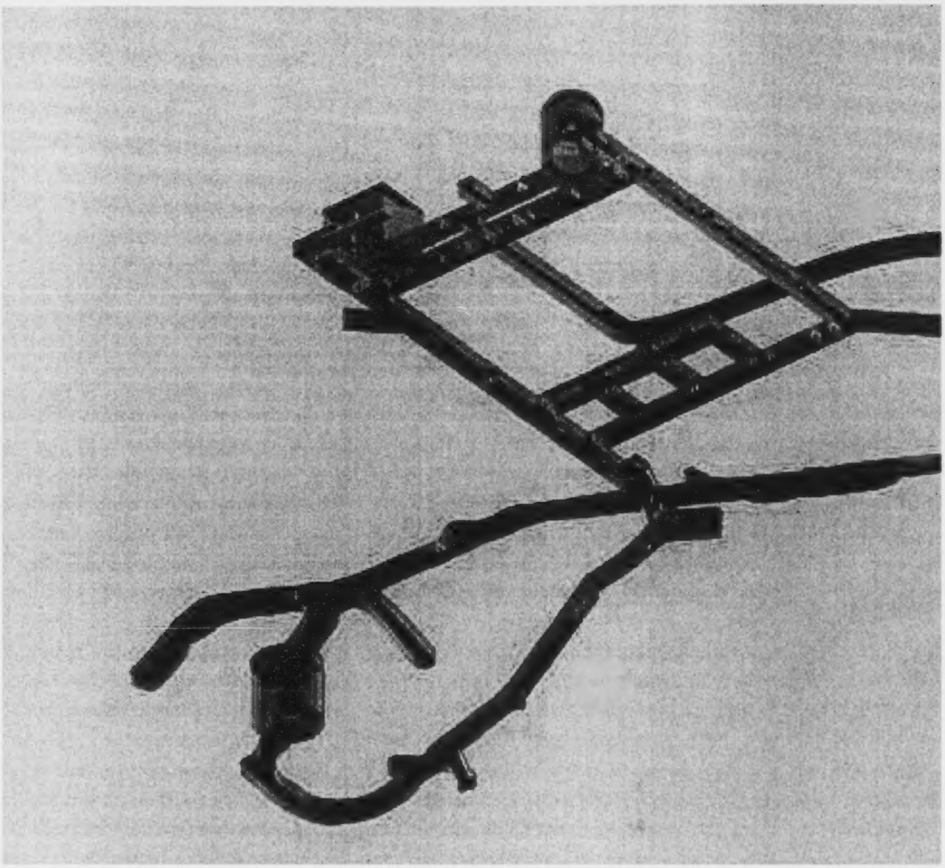
Future Facilities

Over the time period covered by this long-range plan, new or upgraded major facilities will be developed that will modify the global subatomic physics landscape. The timelines for the development of these facilities are uncertain, but they should be considered as the backdrop of any long-range planning process. In some cases, they will involve extending or upgrading existing facilities, such as the ISAC facility, or the ATLAS detector at the LHC.

At TRIUMF, the anticipated strong demand for beams from ISAC will tax the capabilities of the cyclotron in terms of the total circulating intensities and the life expectancy of its radiation sensitive components. The second proton beamline to the ISAC production hall and extensions of the ISAC accelerator complex to provide simultaneous accelerated beams should be a priority. TRIUMF should consider the options for providing higher intensity proton beams to ISAC in the future and should keep abreast of the international effort to develop new high intensity machines.

At the Jefferson Laboratory, a "12 GeV" energy upgrade is planned for the next few years and would enable several new experiments where Canadians will play leading roles.

A major future project, the International Linear Collider (ILC), is currently undergoing an extensive design review process after several years of technical R&D. The technical viability of the design has been proven, and the current goal is to establish a reliable cost estimate for the machine by the end of 2008. The ILC will collide electrons and positrons at an energy of several hundred GeV, allowing precision measurements of new phenomena discovered at the LHC; it has been identified as the highest priority future particle physics

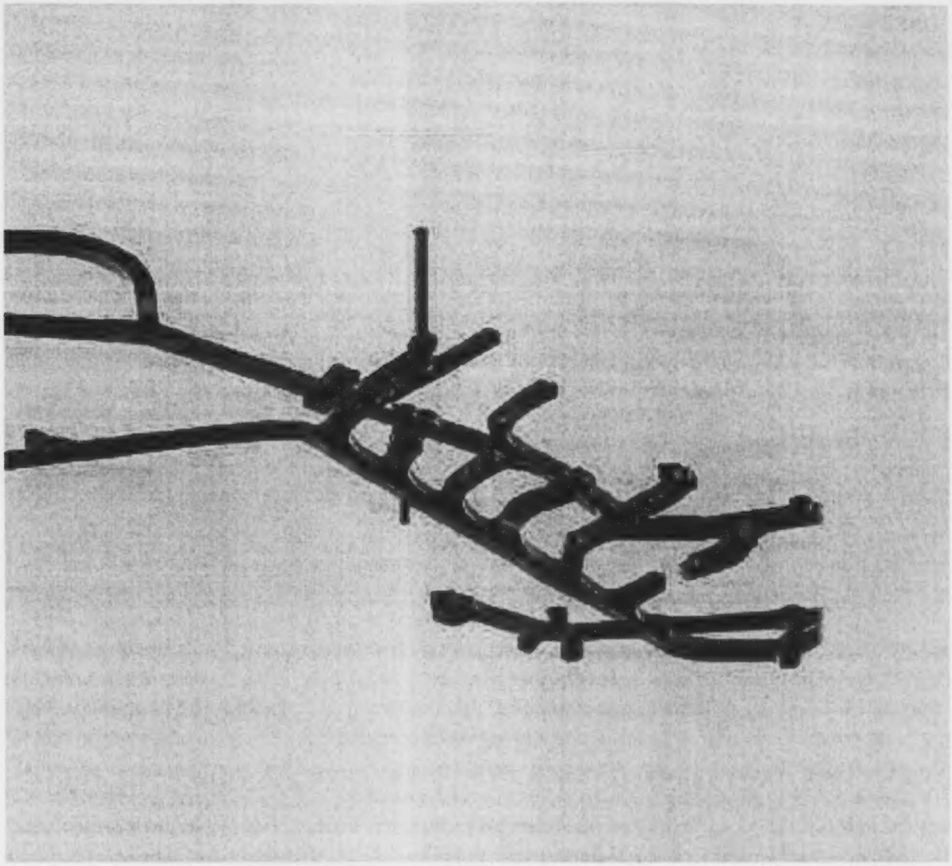


facility by the scientific community. Part of the ILC design review will include a decision on the project site. While the ILC is likely to be located at one of the existing international laboratories, it will require major new international commitments for both the construction of the accelerator and the construction and operation of the detectors. Canadian participation in an ILC experiment in the second five years of this plan will necessitate major capital contributions to a detector and, most probably, to the accelerator itself.

3.2 The Canadian Subatomic Physics Community

The Canadian subatomic physics community consists of nearly 250 researchers based at Universities and labs across the country. It is divided fairly evenly amongst its sub-disciplines of particle physics, nuclear physics, and theory. The subatomic community in Canada has grown since the 2001 long-range plan was prepared, through regular faculty hires as well as new Canada Research Chairs. Approximately one-quarter of the community has joined the Canadian research community over that time, again with a roughly equal split between particle physics, nuclear physics, and theory.

This strong renewal has been accompanied by a healthy increase in the number of students and post-doctoral research associates; graduate student numbers have increased by 55% over the last five years, reflecting the presence of the new researchers and new opportunities.



A schematic layout of the 6800-foot level of the Creighton mine, near Sudbury. The cavern on the far left is approximately 25-m high and houses the SNO experiment; the new SNOLab facility is the square set of tunnels at the top-left of the figure.

Two major new entities in Canadian subatomic physics have come into being during the last five years. The Perimeter Institute for Theoretical Physics, in Waterloo, Ontario, has made a major impact on subatomic theory in Canada. Most scientists employed by the Perimeter Institute maintain adjunct positions at neighbouring universities, and thus are eligible for NSERC funding. As leading researchers in their fields, Perimeter theorists have a major impact on the research and funding landscapes in Canada.

The second of these is SNOLab, for which the Canada Foundation for Innovation (CFI) provided the bulk of the capital funding. SNOLab is a significant extension of the SNO infrastructure in Sudbury, providing Canada with the world's finest deep underground experimental facilities for the coming decades. This is a major facility with the potential to host both national and international experiments requiring low-background environments. Many researchers from the SNO collaboration are engaged in R&D exploring possible techniques for SNOLab experiments, and the facility has attracted interest from researchers in other areas in subatomic physics. The exploitation of this facility will be the focus of substantial discussion of the Canadian subatomic physics program later in this document.

3.3 Accomplishments of the Past Five Years

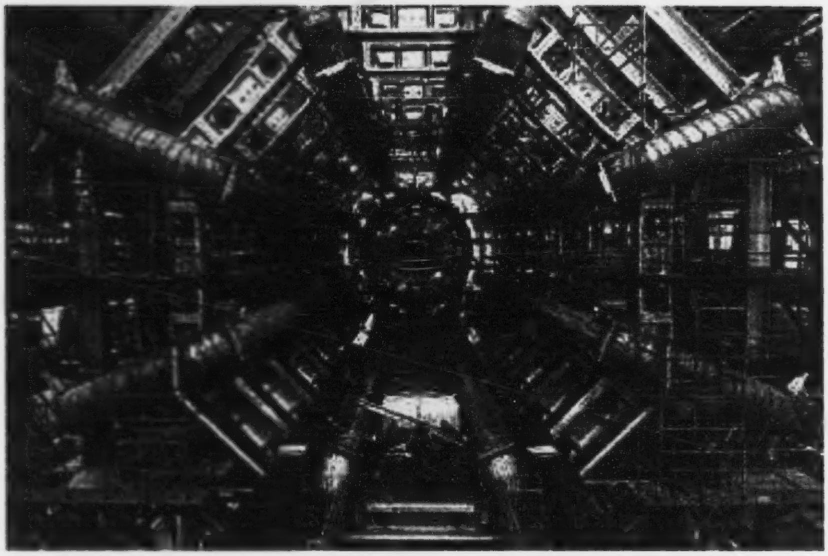
Over the last five years Canadian subatomic physics has concentrated on three high priority projects: building the ATLAS detector to study proton-proton collisions at the Large Hadron Collider (CERN); completing the ISAC-II accelerator and preparing the apparatus to study radioactive isotopes far from stability; and completing the SNO experiment to study neutrinos emitted by the Sun. The significant achievements in each of these areas have been complemented by a broad program of smaller experimental efforts, and by the contributions of a robust and active Canadian theory community.

The Sudbury Neutrino Observatory (SNO) is one of the great success stories of Canadian subatomic physics. SNO's resolution of the solar neutrino problem has received world-wide attention. Their measurements of the total neutrino flux from the Sun are in excellent agreement with solar model calculations, strengthening the belief that the standard solar model is a correct description of stellar evolution. SNO has conclusively resolved the "Solar Neutrino Problem", demonstrating that about 2/3 of the electron neutrinos produced in the Sun "oscillate", changing to other types of neutrinos before reaching the Earth. Further, SNO's results taken together with other solar and terrestrial measurements indicate that these oscillations are mass-driven. The measurements have helped constrain the mass-difference and mixing angle – critical and fundamental parameters in our understanding of neutrino physics – that explain these oscillations.

The ISAC hall at TRIUMF has been operational since 2001, and ISAC-II is nearing completion. Together they are the world's premier radioactive beam complex. This field of nuclear physics and nuclear astrophysics with short-lived exotic nuclei is globally recognized as being of the highest priority. Several important results have already emerged from ISAC. An example is the measurement of the production of magnesium from ^{21}Na, a reaction [1] that is responsible for the galactic abundance of ^{22}Na produced in explosive stellar environments. This measurement resolves the long-standing problem of the non-observation of ^{22}Na in data from gamma-ray satellite instruments.

The Large Hadron Collider at CERN will provide the ATLAS experiment with the highest energy proton-proton collisions on Earth, where we expect to see the resolution of the Standard Model explanation of the origin of mass. The ATLAS Canada group has now completed construction and installation of the detector components for which it was responsible, and is very active in the commissioning of the ATLAS experiment. This activity continues to grow as Canadian researchers move to ATLAS in greater numbers, preparing for first beam in 2007. The activities of ATLAS physicists are increasingly focused on the extraction of physics from the first data, and on the computing which will be necessary to handle the influx of data.

[1] The exact reaction is $^{21}\mathrm{Na} + p \rightarrow \gamma + {}^{22}\mathrm{Mg}$, written $^{21}\mathrm{Na}(p,\gamma)^{22}\mathrm{Mg}$.



The partially-assembled ATLAS detector at CERN's LHC accelerator, as it appeared in late 2005. To set the scale, note the man standing at the bottom-centre of the photograph.

3.4 Our Vision for Canadian Subatomic Physics Research

Canadian subatomic physics is in a position of strength and has an excellent record of accomplishment. The task for the next five years is clear: we must build on our human assets, our world-leading facilities, and our recent accomplishments to remain global leaders in our science. In the short-term we must exploit the facilities and experiments that we have helped to develop, emphasizing the highest energies available (ATLAS), nuclear physics and nuclear astrophysics (ISAC), and neutrino physics (SNOLab and T2K). Our exploitation of these facilities must be commensurate with our past investment – both human and capital – and we must be leaders in extracting the exciting new physics which will emerge.

In the longer term, we must recognize that advancing our science depends on continued R&D for future projects, and that the most promising of these projects will require major capital investment. The largest of these projects is already on the horizon: in the second five years of this plan the International Linear Collider will be a reality, and Canadian subatomic physics must pursue a vigorous program of R&D to position ourselves to play a prominent role in it.

Given the size of our community, we cannot be involved in all subatomic physics endeavors. However, maintaining diversity in Canadian subatomic physics is necessary for the health of our discipline. That diversity, in the form of a number of smaller projects, allows us to retain the flexibility necessary to identify and pursue new opportunities as they emerge.

This strategy – investing the bulk of our resources in a small number of high priority projects, while maintaining a diverse suite of smaller efforts – has, in the past, proven to be a winning recipe. Canadians have held key roles as spokespersons, deputy spokespersons, physics chairpersons, run coordinators and physics group leaders in nearly all of the experiments in which we have been involved.

Our vision has the following high priority endeavors for Canadian SAP over the next decade:

- Full exploitation of the potential for new physics discoveries in the highest energy proton-proton collisions on Earth using the ATLAS detector;
- Completion and full exploitation of the world's premier radioactive beam facility at ISAC (TRIUMF) for nuclear physics and nuclear astrophysics;
- Completion of the SNOLab facility and its development into the world's lowest-background laboratory, including capital participation in a suite of experiments to exploit this unique environment;
- Participation in a long-baseline neutrino oscillation program;
- R&D for major involvement in the ILC, including participation in the international deliberations concerning its timing and location.

We expect that approximately 75% of the subatomic physics community in Canada will be involved in the programs listed above. Participation in a diverse program assures the long-term health of our discipline, and we therefore also recommend as a high priority:

- Maintenance of a diversity of research efforts, allowing the community to exploit new opportunities and novel ideas as they arise.

This broad program will help to continue to attract the brightest researchers into the field in Canada, and may well provide new efforts that emerge as major components of the SAP program in the future.

We believe that this vision will position us at the very forefront of our science, participating in the excitement that will emerge from projects currently underway, and leading the new projects that will exploit the discoveries made there.

4
Addressing the Fundamental Questions: The Canadian Program

Two notable features of subatomic physics are its fundamental nature and the overarching Standard Model that describes it. Key questions are probed through a variety of complementary approaches, spanning a spectrum from low-energy nuclear physics to high-energy particle physics. A close relationship between theory and experiment is also essential and the Canadian program is a well balanced mixture of theory and experimental efforts.

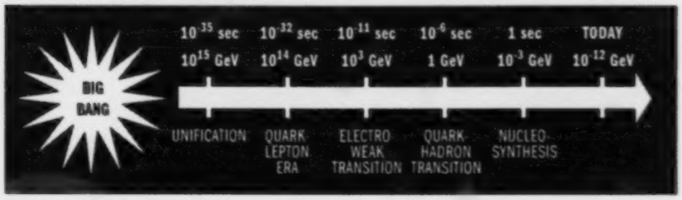
Canadian subatomic physicists conduct their research at facilities in Canada and around the world. Their scientific leadership coupled with innovative design and technology has led to major discoveries, theoretical advances, and precision measurements of critical processes. In this section we highlight some of those recent achievements and outline a balanced program for the next decade that will build on our strengths and have a significant impact in advancing subatomic physics.

4.1 The Current Status of Subatomic Physics

The goal of research in subatomic physics is to understand the evolution of the Universe and the matter within it. The Universe began with a cosmic explosion known as the Big Bang. This extremely hot and dense early Universe gave rise to a sea of particles in constant interaction with one another. The Universe has since cooled, and these particles have long since decayed away, annihilated into

radiation or condensed into nuclear matter. The world of the large (cosmology) and the small (particle and nuclear physics) are closely interconnected because the properties of particles and nuclear matter defined the conditions in the early Universe from which the cosmological structures formed.

Time-line representing the sequence of events following the Big Bang

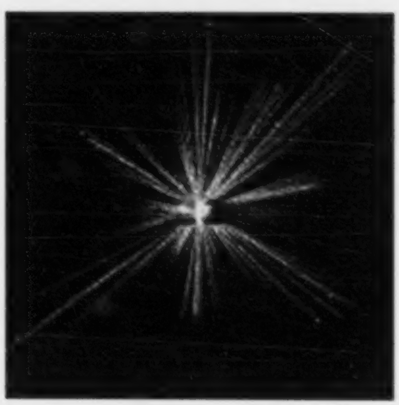


From a subatomic physics point of view, much of the interesting physics is contained in the first seconds following the Big Bang. At the earliest times, all of the interactions in the Universe are thought to have been united in a single force. As the Universe cooled and expanded, it went through many phase transitions. Following the rapid expansion of the Universe, it became a very hot soup of particles: the fundamental quarks and leptons. Later, the quarks condensed into bound states (hadrons), and eventually at about 1 second, nuclear matter was produced.

In order to understand the particles and matter that existed during these various epochs, we recreate them in laboratories using accelerators. Physicists in Canada working in the sub-disciplines of nuclear physics, particle physics, and particle astrophysics probe all of the physics depicted in the time-line, an understanding of which addresses the fundamental questions raised in Section 2. In this section, we provide a brief introduction to subatomic physics, and then illustrate how the Canadian program is making progress in addressing the fundamental questions with complementary approaches.

In the Standard Model (SM), there are three families of quarks (u,d), (c,s), (t,b),[2] charged leptons (e,μ,τ) and neutral leptons (the neutrinos: ν_e,ν_μ,ν_τ) (see Figure 1). There are also the mediators of the electromagnetic, weak and strong forces,

An artist's depiction of a high-energy electron-positron collision, in which many secondary particles are produced.



[2] The quark type is referred to as the "flavour".

namely the photon (γ), $W^{\pm}$and Z^0 bosons, and the gluons. The electromagnetic force is familiar in everyday life. The weak force is visible through radioactive decay, and the strong force holds quarks together within the proton and neutron (and other hadrons).

Subatomic particles

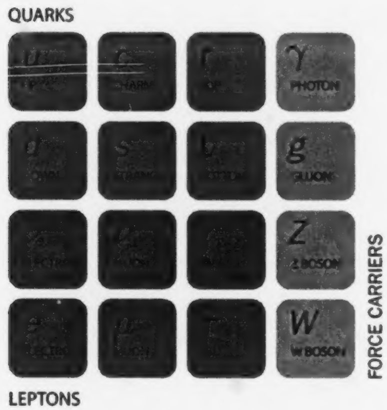


Figure 1: The three families of quarks and leptons in the Standard Model.

At high energies the electromagnetic and weak forces unify to form the Electroweak interaction. Several Nobel Prizes have been awarded for these theoretical developments and the elegant experiments which confirmed them. The theory of the strong interactions is known as Quantum Chromodynamics (QCD). The Electroweak forces and QCD describe all interactions within the Standard Model, which can be tested by measuring the properties and detailed interactions of the quarks, leptons, and mediator bosons. Precision tests have so far failed to find any conclusive flaws in the Standard Model.

Physicists have established that the SM describes most matter and its interactions extremely well. The ongoing task is to obtain a deeper understanding of the applicability of the SM to a wider range of phenomena. There are also unresolved questions – one being how particles are endowed with mass. In the Standard Model, the Higgs mechanism gives rise to the masses of fundamental particles. The Higgs boson is the only Standard Model particle which has not been observed directly. No clear Higgs signal was observed in experiments at the LEP collider at CERN and this, combined with precise measurements of the top quark mass, has put tight constraints on the allowed mass of the Higgs boson. The Higgs sensitivity may be extended at the Tevatron collider at Fermilab which has a higher reach in energy than the LEP collider, but the definitive test will come from experiments at the LHC which should discover the Higgs if it exists in the predicted form. Discovering the Higgs particle and investigating its properties are primary aims of the ATLAS experiment.

Symmetries of nature are particularly important in subatomic physics. Symmetries result in conservation laws, such as conservation of momentum and energy. We obtain a deeper insight into the interaction processes by understanding the nature and origin of these conservation laws. In certain systems the symmetries

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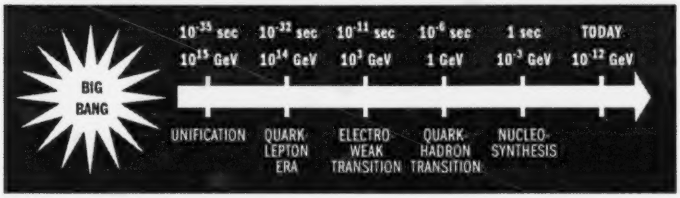

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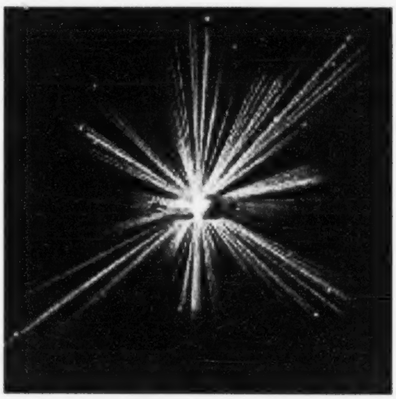

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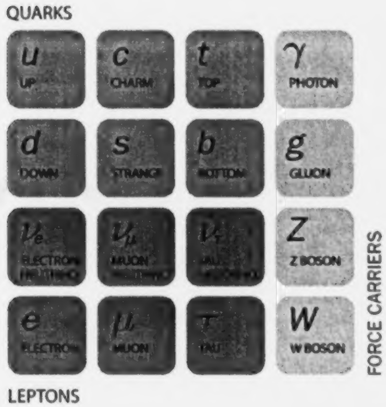

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are broken, and the conservation laws are no longer valid. Understanding why and how these symmetries are broken offers great insight into those physical processes. Three particularly relevant symmetries are: P invariance, which implies that the laws of physics are invariant if all spatial coordinates are reversed (opposite Parity); C (Charge conjugation) invariance which demands physics be identical for particles and antiparticles; and T invariance which ensures that the laws of physics are reversible in time. From fundamental principles, the combination of these three symmetries, CPT, is thought to be an invariant for all types of interactions.

The strong and electromagnetic interactions are invariant under the operation of P and C and of the dual operation CP. Weak decays violate P and C but only in rare instances is the combination CP violated, with interesting consequences. The observation of CP violation in the neutral kaon system led to the 1980 Nobel Prize and studying similar processes in other particles (B mesons and neutrinos) is one of the fundamental quests of subatomic physics today.

Understanding the basic properties of matter and antimatter is a key to understanding how the Universe evolved from the Big Bang. In particular, the observation that we live in a matter dominated Universe implies that at some time after the Big Bang there were physical processes that resulted in a tiny, but non-zero, amount of matter in excess of antimatter that could not annihilate completely. The resulting baryon asymmetry is known as baryogenesis. CP violation allows for different behaviours of matter and antimatter and the Standard Model can accommodate CP violation in the quark sector. However it appears insufficient to account for the observed baryon asymmetry in the Universe; some other process must be responsible. Because CPT is believed to be invariant, violation of CP then implies that T must be violated. There is a global effort to understand the implications and origins of CP (or T) violation, in both quark and lepton systems.

An interesting property of the weak interactions is that quarks "mix", or transmute between one flavour and another. In weak interactions, quarks are quantum mechanical admixtures of different flavoured states. The degree of mixing is encapsulated in the Cabibbo-Kobayashi-Maskawa (CKM) matrix, whose elements describe the fraction of each admixture. Measurements of these matrix elements has been a substantial part of the global accelerator-based research effort. In addition, precise measurements of many CKM matrix elements come from nuclear physics experiments, and these are a significant part of the program at radioactive beam facilities such as ISAC.

The 2002 Nobel Prize was awarded for the study of extraterrestrial neutrinos. Neutrinos are abundant and are produced in the Sun, in radioactive nuclei in the earth, in nuclear reactors, by interactions of cosmic rays in the atmosphere, and through astrophysical activity. Recent discoveries from underground detectors such as SNO have definitively demonstrated that neutrinos have mass and are able to mix. This has presented new challenges and opened up a rich new field; we have only started to understand the properties of neutrinos. Measuring the parameters of the neutrino mixing matrix is the subject of intense efforts world-wide. Unlike quarks, neutrinos appear to mix quite strongly. If the neutrino is its own antiparticle, this leads to the exciting possibility of large CP violation in

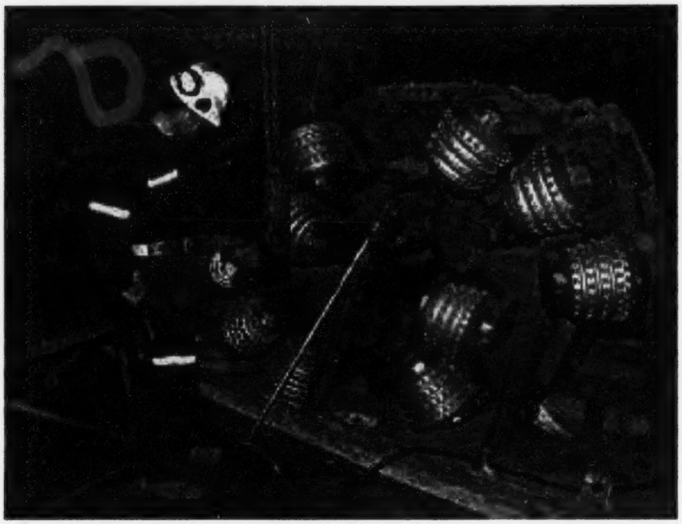
the neutrino sector which, combined with quark-lepton couplings at very high energies, could ultimately explain the observed matter-antimatter asymmetry of the Universe.

Although the Standard Model has been extremely successful at describing the world we live in, it does not explain from first principles the many parameters necessary in the model. It cannot accommodate dark matter, and the origin of light neutrino masses is problematic in many theories. These experimental hints, plus the development of unified theories where the electromagnetic, weak, and strong couplings unify at a high energy scale, suggest that the Standard Model is a low energy approximation of a more general theory. One such well-motivated theory is supersymmetry, which predicts that many new particles will be observable at LHC energies. These unobserved particles could have existed at the very high energies in the early Universe and perhaps obeyed laws of physics different from those applicable in the cold Universe of today. Indirect signatures of new physics at the TeV energy scale may also be provided by nuclear physics through precision measurements of Standard Model observables or observation of phenomena forbidden or suppressed in the Standard Model.

Astronomical measurements have recently revealed that only a small fraction of the total mass of the Universe is formed of luminous matter (like stars). Galaxy rotation rates can only be explained by Einsteinian/Newtonian gravity if 80% of their mass consists of dark matter that emits no radiation and hence is not visible. This conclusion is supported by the most recent high-precision studies of the cosmic microwave background. Accounting for dark matter is crucial, and searching for it spans the fields of cosmology, subatomic physics and astrophysics.

If supersymmetry is a valid theory, a very appealing possibility is that a non-decaying, lightest supersymmetric particle could be the dark matter. Dark matter searches will be the focus of several experiments at SNOLab.

Inside TRIUMF's 500 MeV H^- cyclotron, the world's largest cyclotron.



A tunnel boring machine used to excavate the new SNOLab facility in the Creighton mine. ion text caption text

Quarks and gluons combined to form hadrons at $t \sim 10^{-6}$ s after the big bang. The theoretical framework describing the interactions of quarks and gluons is QCD. At short distances, or high energies, the quark-quark interaction is very weak. The 2004 Nobel Prize was awarded for the elucidation of this "asymptotic freedom". Calculations for processes in this regime are reliable and have established QCD as a robust theory. At long distances (as in scattering experiments), the quark-quark interaction strength becomes very large. No free quarks have ever been observed, and the mechanism for confinement is a very active area of study in strong interactions, both experimentally and theoretically. Advances in QCD calculational techniques, as well as new precision experimental data, could revolutionize our understanding of the structure of hadrons.

As the Universe cooled further, it entered the phase of primordial nucleosynthesis – the formation of nuclei such as H, He, and Li. All other elements in the Universe were produced as a result of nuclear reactions occurring in stars, supernovae explosions, novae, and neutron-star mergers. There are many open questions related to the origin of matter in the Universe. These include a detailed understanding of the origin of the elements; the mechanism of core-collapse in supernovae; the structure and cooling of neutron stars; the origin, propagation, and interactions of the highest-energy cosmic rays; and the nature of galactic and extra-galactic gamma-ray sources. Answers to those key questions are expected from improved astrophysical models, refined computational simulations, observational breakthroughs, and from a better understanding of the underlying nuclear physics.

Many key questions are intimately coupled to the properties of matter under extreme conditions, such as the very high densities and temperatures, and extreme proton-to-neutron ratios, in explosive astrophysical environments.

Under such conditions, very short-lived exotic nuclei are produced which play decisive roles in key astrophysical processes. Enormous progress has been made at radioactive-beam facilities dedicated to the measurement of the structure and reactions of nuclei relevant to astrophysics. These include measurements of the various nuclear capture processes and the determination of masses, half-lives, and structures of rare nuclei that exist in cataclysmic stellar environments, such as novae or supernovae explosions. The aim is to reconstruct the scenarios in detail and study the interactions in a laboratory. Canadian scientists are ideally situated to make new discoveries and exploit this physics using ISAC at TRIUMF, the world's most advanced radioactive-beam facility.

4.2 Physics of Neutrinos

Solar Neutrinos

One of the most outstanding recent discoveries in the electroweak sector has been the observation that neutrinos have mass, conclusively demonstrated by the Sudbury Neutrino Observatory (SNO). For over thirty years, using a variety of experiments with sensitivities to different parts of the neutrino energy spectrum, scientists have measured a deficit of neutrinos coming from the sun. The observed rate of electron neutrinos (the type produced by the Sun) arriving at the earth was approximately one-third of the total number predicted by the standard solar model. This long standing problem, dubbed the "solar neutrino problem" catalyzed enormous developments in more refined models of stellar processes, but the enigma persisted.

Unlike earlier experiments, SNO had the unique capability of being simultaneously sensitive to electron neutrinos through one reaction, and to all neutrino flavours through another. By comparing these reaction rates, SNO demonstrated that neutrinos born as electron neutrinos transmuted from one type to another en route to the Earth. This behaviour, called "oscillation", is only possible for massive neutrinos. SNO also found that the total number of neutrinos emanating from the Sun agrees very well with the detailed solar model predictions, implying that the fusion reactions in the Sun are well understood. The results from SNO have had wide reaching implications, and the first three papers presenting them have received over 3000 citations.

The neutrino oscillation data can be described by a three neutrino mixing scheme, in which the flavour states $\nu_\alpha (\alpha = e, \mu, \tau)$ are related to the mass states ν_i (where i=1,2,3) through a unitary lepton mixing matrix, the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix (Figure 2). The results from SNO, combined with results from the Super-Kamiokande experiment and accelerator-based experiments, have put severe constraints on the allowed neutrino mixing angles θ_{ij}, and the mass differences Δm^2_{ij}. It is found that θ_{12} and θ_{23} are large, in contrast to the small mixing angles measured in the quark sector. The masses of neutrinos appear to be very small, and so cannot be a significant portion of the missing dark matter in the Universe. This also suggests that the Universe will likely expand forever, rather than gravitationally collapsing on itself in a "Big Crunch".

The SNO experiment will finish operations in December, 2006. A proposed new experiment, SNO+, would replace the heavy water in SNO with liquid scintillator to study the low energy ("*pep*") solar neutrinos. The *pep* flux is calculated to ±1.5% in the standard solar model, and hence has the potential to vastly improve the precision on the mixing angle θ_{12}. At high energies, such as for the ^8B neutrinos observed by SNO, it is expected that neutrino propagation in the sun is dominated by resonant interactions with matter (the MSW effect). However, other mechanisms such as non-standard neutrino interactions, mass varying neutrinos, sterile neutrino admixtures, and *CPT* violation have been proposed. At *pep* energies, the neutrinos are highly sensitive to the specific mechanism, and probing this region is essential to understand the physics behind neutrino oscillations. The SNO+ experiment could also measure geo-neutrinos from natural radioactivity in the earth, providing geologists with a measurement of the distribution of radioactivity in the Earth. The SNO+ experiment would utilize the existing SNO detector and infrastructure, build on the expertise of the SNO collaboration, and have a significant impact on our knowledge of neutrino properties.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta CP} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta CP} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta CP} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}c_{13}c_{23}e^{i\delta CP} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta CP} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Figure 2: The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix governing neutrino oscillations. $s(c)_{ij}$ represents $\sin(\cos)\theta_{ij}$ etc.

Accelerator-Based Neutrino Experiments

As mentioned above, the angles θ_{12} and θ_{23} are now reasonably well determined through studies of solar, reactor, and accelerator neutrinos. The next major thrust in this field is a determination of θ_{13}, thought to be very small. The SNO experiment will constrain this quantity somewhat by improved measurements over the next year, but ultimately a dedicated long baseline neutrino oscillation experiment is required.

Canadian physicists are involved in the T2K (Tokai to Kamioka) experiment that will make use of the J-PARC accelerator facility in Japan. This facility will provide an intense beam of low-energy off-axis muon neutrinos with a narrow energy spread and only a small high energy tail. With some knowledge of the PMNS mixing elements, it is possible to optimize the discovery potential by selecting a beam energy matched to the experimental baseline. The goal of the T2K experiment, in the first five years of running, will be to observe the transition of ν_μ to ν_e, providing evidence that $\theta_{13} \neq 0$. If the neutrino is its own antiparticle, large *CP* violating phases are possible, which could lead to an explanation of the baryon asymmetry of the Universe.

If θ_{13} is found to be sufficiently large, a later phase of T2K is envisaged with upgraded accelerator beam power and the construction of a 1 megatonne water Cerenkov detector (Hyper-Kamiokande) at the Kamioka site. This would

A map of the central part of the island of Honshu, Japan, showing the paths of the neutrino beams for the K2K and T2K experiments.

improve sensitivity to ν_μ to ν_e oscillations, and possible *CP* violation in the neutrino sector, by an order of magnitude. In the longer term, high intensity neutrino sources based on stored muon beams are being investigated at several facilities. This is a new and growing field, spurred by the SNO confirmation that neutrinos have mass. There is great potential for exciting new physics to be discovered during the coming decade.

Neutrinoless Double Beta Decay

While neutrino oscillation experiments, such as those made at SNO, have shown that neutrinos possess mass, they do not measure the mass directly. The best limits from direct measurements of tritium beta decay give $m_{\nu_e} < 2.2$eV. This is still much higher than the anticipated neutrino masses and novel new measurement techniques are required. Certain nuclei may decay via the very rare neutrinoless double beta decay process. The rate depends on the neutrino mass, and experiments worldwide are searching for this process. Only a handful of nuclei are energetically allowed and the rates are expected to be less than one decay per kilogram-year and possibly of order one decay per tonne-year. These studies require detailed understanding of nuclear matrix elements and will be complemented by ISAC experiments and by advances in nuclear theory.

The process is only allowed if neutrinos are their own antiparticles. For such Majorana neutrinos, large *CP* violating phases are possible, which again leads to the possibility of explaining the matter-antimatter asymmetry in the Universe. The observation of neutrinoless double beta decay would definitively establish the Majorana nature of neutrinos.

The smallness of neutrino masses has been an enigma. Majorana type neutrinos are natural in favoured theories which predict light neutrinos due to a coupling with very massive right handed neutrinos. In this scenario, understanding the physics of light neutrinos would provide insight into physics at the highest of energy scales.

There is one highly controversial observation of neutrinoless double beta decay, which favours neutrino masses of 0.2-0.6 eV. Definitive observations in more nuclei are required. The search for these processes requires very large detectors and the ultimate in low background materials and techniques. The low background

environment of the SNOLab facility makes it an ideal location to perform such measurements. The EXO and Majorana collaborations are currently developing experiments that will search for neutrinoless double beta decay in xenon and germanium, respectively, and are pursuing siting their experiments at the SNOLab facility. An early goal of these experiments is to confirm or refute the present claim; in the longer term the goal is to reach sensitivities of order 50 milli-eV in effective neutrino mass.

The new surface building of the SNOLab facility near Sudbury, housing offices, meeting rooms, and laboratory space.

4.3 Nuclear Astrophysics Studies

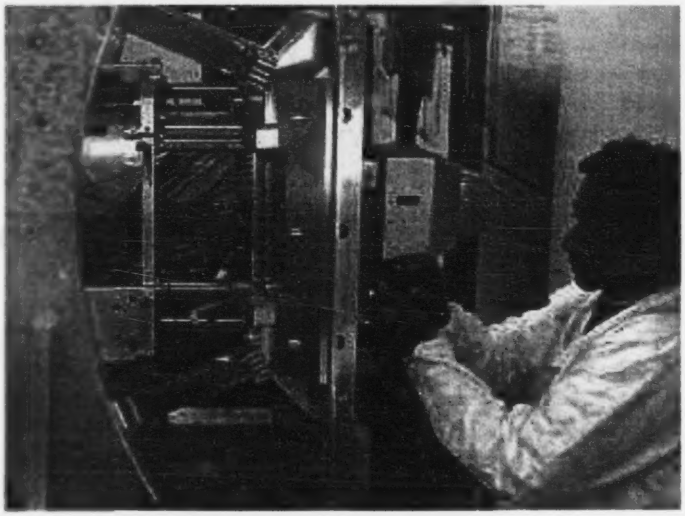
The production of heavy elements occurs in the incredibly hot nuclear furnaces found in stellar cores and stellar explosions. These processes involve highly exotic isotopes at very high temperatures. Using radioactive beams one can explore this large 'terra-incognita' in order to understand complex nuclear systems and physical processes occurring in stellar environments. One such area of research is a detailed understanding of energy production and nuclear synthesis in stars. The larger a star's mass, the higher the temperature that can be reached in the stellar core; this has critical implications on the nuclear processes that can occur. For temperatures from $\approx 10^6$ K to 10^7 K, energy production takes place primarily via the *pp* chains that convert hydrogen into helium. At ever increasing temperatures, ^4He fuses to form ^{12}C and the CNO cycle produces the bulk of the energy. Then the Ne-Na and Mg-Al cycles occur and eventually, at several 10^9 K, the burning endpoint of $^{56}Ni/^{56}Fe$ is reached. The end of each burning cycle is accompanied by partial stellar collapse and subsequent reheating of the core. An understanding of all these processes is essential to understand stellar evolution in detail and the explosive environments found in novae and supernovae.

Canadian physicists working at the ISAC facility at TRIUMF play a key role in this active field of testing matter under extreme conditions. ISAC provides ideal conditions to carry out these experiments, and state-of-the-art detectors including the unique DRAGON spectrometer, the TUDA and 8π facilities, and TITAN. This program is complemented by experiments underway in Europe, but ISAC is recognized as the world's leading facility for the production of exotic isotopes.

A major accomplishment of the Canadian community has been the determination of the rate of $^{21}Na(p,\gamma)^{22}Mg$, a key reaction that determines the abundance of galactic ^{22}Na produced in explosive scenarios, such as novae or X-ray bursters. Previously, it was believed that ^{22}Na production would be sufficient to allow it to be detected by γ-ray astronomy via its primary decay. A major dilemma was the fact that neither the COMPTON nor the INTEGRAL satellites observed it. Direct measurements of this reaction, performed using a beam of ^{21}Na with the DRAGON spectrometer at ISAC, measured the $^{21}Na(p,\gamma)^{22}Mg$ reaction rate to be higher than previously estimated. This results in ^{22}Na production much earlier in the nova where it is effectively removed by the $^{22}Na(p,\gamma)^{23}Mg$ reaction, in agreement with the observations of the γ-ray satellites and the standard model of stellar evolution.

New detectors, such as EMMA and TIGRESS, presently under construction for use with the accelerated beams at ISAC-II, will play key roles in this program and ensure that TRIUMF stays at the forefront of this area of research. In the future, the DRAGON, TUDA, and TACTIC spectrometers at ISAC-I will focus on nuclear astrophysics measurements in light ($A < 30$) proton-rich systems, and TITAN will measure the masses of unstable nuclei of astrophysical interest. The TIGRESS and EMMA spectrometers will make use of the higher energy ISAC-II beams to study the structures and reactions of neutron-rich nuclei necessary to understand the production of the heavy elements in rapid neutron-capture nucleosynthesis.

The synergy between advances in theoretical and experimental nuclear physics and astrophysics has already had a significant impact on how we understand the energy production in the life and death of stars. The measurements planned will bring us much closer to further resolving the secrets of the Universe.



Installation of the first gamma-ray detector of the new TIGRESS spectrometer developed for the ISAC-II accelerated radioactive ion beam facility.

4.4 Nuclear Structure Studies

Nuclear matter forms most of what we see around us. Ironically, the complexity of this matter is such that physicists know more about exotic particles produced in the early Universe than they do of nuclear matter. To understand the interactions between nucleons of many-body systems, such as ^{208}Pb, based on the underlying dynamics of quarks and gluons, is intellectually and technically challenging. In the past, research has been restricted to investigating stable nuclei of varying Z (atomic number), a "one-dimensional" view of the nuclear Universe. Radioactive beam facilities produce and accelerate neutron-or proton-rich isotopes, allowing the nuclei of interest to vary in Z and N (neutron number). This two-dimensional approach allows a variety of exotic nuclei to be investigated, shedding new light on elements of nuclear structure. Unexpected phenomena, such as neutron "skins", may appear in very neutron-rich nuclei. In light-mass nuclei they can form halo systems – nuclei where some of the valence neutrons have a spatial extent that greatly exceeds the expected nuclear dimensions. One of the first examples of this phenomenon was ^{11}Li. With 3 protons and 8 neutrons, it is nearly as large as the much more massive ^{208}Pb.

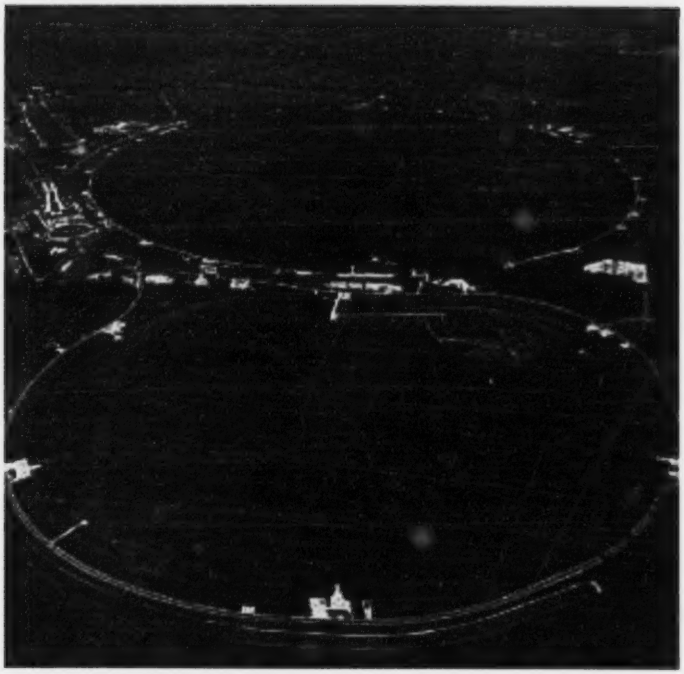
During the past five years, the 8π spectrometer has been installed at ISAC. Augmented with auxiliary detectors, it is a unique device optimized for the study of radioactive isotopes. An early highlight from the 8π spectrometer was a measurement involving the β-decay of ^{11}Li. A surprising result was evidence that the neutron halo structure, rather than being "fragile", could not only survive the process of β-decay from ^{11}Li to ^{11}Be, but also the ^{11}Be neutron emission to ^{10}Be. It has been proposed that the extra stability is mediated by the exchange of low-frequency surface vibration modes of the nucleus, and confirmation of this mechanism would lead to the understanding of the ^{11}Li halo as an isolated neutron Cooper pair. These systems thus provide an ideal tool for understanding the origin of the collective pairing interaction in nuclei – the same pairing mechanism that manifests itself as superconductivity in heavier systems.

The future nuclear structure program at ISAC will be centred on the 8π Spectrometer and TITAN for decay spectroscopy and mass measurements at ISAC-I, and the TIGRESS and EMMA spectrometers currently being installed at ISAC-II. These latter spectrometers represent major steps forward in γ-ray detector technology and nuclear recoil detection and will be employed in a broad program of nuclear structure and reactions research with the higher-energy radioactive beams from the new ISAC-II accelerator.

4.5 Direct Standard Model Tests at Colliders

Precision Electro-Weak tests at LEP, HERA and the Tevatron

Two decades of extensive testing has firmly established the validity of the Standard Model. At higher energies, new physics is anticipated, but precision tests at lower energies can also probe subtle effects of physics beyond the Standard Model. Hence a great deal of effort of Canadian physicists at the HERA, LEP, and Tevatron colliders has gone into testing the Standard Model, measuring free parameters, and searching for evidence or hints of new physics.



Aerial view of the Fermi National Accelerator Laboratory (Fermilab) near Chicago. Both the Main Injector (near ring) and the Tevatron are clearly visible.

Literally hundreds of measurements of Standard Model parameters have been made in these collider programs. Highlights include the precision measurement of the mass and width of the Z^0 at LEP, from which it was determined that there are exactly three families of light active neutrinos. The mass and width of the W boson were also measured with great precision by LEP and Tevatron experiments. The most significant Tevatron result was the discovery of the top quark with a surprisingly large mass of 172.5 GeV. The top quark mass is measured to a precision approaching one percent, making it the best measured of all quark masses; when combined with the W boson mass these measurements provide the best current limits on the Higgs boson mass, and favour a small mass. A significant HERA result has been the demonstration of electroweak unification through charged and neutral current measurements at high Q^2. New data with polarised leptons will provide precision tests of the chiral nature of such interactions.

Numerous precision tests have been performed to search for evidence of new physics beyond the Standard Model. These have included searches for composite particles, excited lepton states, leptoquark combinations and large extra dimensions. No evidence for any of these has been found. Particle couplings have also been investigated in a search for new physics. As an example, the couplings of the W boson to its neutral partners, the γ and Z, are sensitive to deviations from the Standard Model, but no deviations have been seen in measurements at LEP, the Tevatron, or HERA.

Canadian participation at LEP, HERA and the Tevatron has been very strong. The collider program has made exciting new discoveries, and explored and refined every facet of the Standard Model. We will continue to reap the benefits of this rich physics program through the end of the decade. As the Tevatron and HERA programs wind down, participation in the ATLAS effort is building up, with the exciting prospect of new physics just around the corner.

Higgs and supersymmetry searches at the LHC

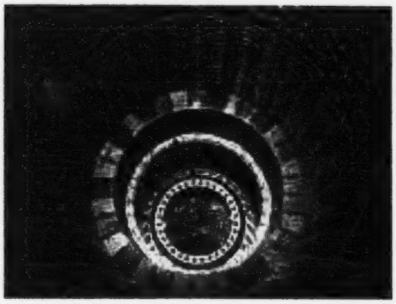
The Large Hadron Collider is nearing completion, and first data are expected by the end of 2007. The proton-proton collisions will have a centre of mass energy of 14 TeV, providing enough energy to produce many new particles. One of the main goals is the search for the Higgs boson. The current data, in particular the mass of the top quark, constrain the mass and strongly favour a light Higgs. If it exists, the Higgs should be observed rather soon after the LHC comes on line. The ATLAS experiment will be sensitive to Higgs with masses up to 1 TeV, well beyond current expectations.

Supersymmetric theories predict the existence of new particles and processes at energies accessible at the LHC, and the search for these supersymmetric particles will be one of the main goals of ATLAS. Other theories and extensions to the Standard Model also predict new states which could be observed by ATLAS, including excited fermions, composite objects and leptoquarks. Through their active contribution to the ATLAS experiment, Canadians are involved in all of these 'discovery-potential' searches.

The connection between theory and experiment is particularly important for LHC physics. Theorists have played an essential role in identifying experimental signatures for physics beyond the Standard Model, and in optimizing the LHC's discovery potential. This partnership will continue as the accelerator starts operations and the interpretation of interesting new findings begins.

Some of the more than 1800 scientists from around the world who are members of the ATLAS collaboration.

A view of the ATLAS Hadronic Endcap Calorimeter prior to installation. The HEC was constructed in Canada and assembled at TRIUMF.



Beyond the Standard Model at the International Linear Collider

The ATLAS experiment is likely to provide revolutionary discoveries, but these will certainly introduce additional questions. While it appears the Standard Model Higgs boson must be quite light, the theory would naturally predict quantum mass corrections that would produce a very heavy Higgs boson. Theorists have already posited a vast array of symmetries that would explain why the Higgs must have a mass similar to the *W* and *Z* bosons. It is only by studying the new particles found at the LHC, measuring precisely their masses and lifetimes, and determining their couplings to Standard Model particles with high precision, that we will be able to distinguish between possible particle physics scenarios.

The proposed International Linear Collider (ILC) will collide electrons and positrons with beam energies up to 500 GeV and provide access to states up to 1 TeV in mass. Since electrons are point-like particles they provide cleaner collisions than those of hadron colliders, greatly facilitating mass and branching ratio measurements. However, the proton-proton collisions of the LHC are less restrictive in terms of quantum numbers for initial states, and so compare favourably in the determination of particle spins and the hierarchy of states associated with the production of new particles. The complementary approaches of the LHC and the ILC will be essential to fully clarify the physics beyond the Standard Model.

As discussed in detail in the following sections, precision measurements of coupling constants, masses and symmetries can provide insight to physics at energy scales well beyond the energies available in a collider. The ultimate goal of particle physics is the understanding of how the different forces – electroweak and strong – could be unified and explained by a single theory. Current measurements indicate that this does not occur at energies below 10^{13} TeV. The precision available at the ILC will make it possible to refine measurements of the Standard Model couplings and allow us to extrapolate predictions with sufficient precision to limit the possibilities for the unification of the forces. Unless the physics between here and the TeV-scale is particularly simple, it will only be possible to make these extrapolations with confidence with ILC measurements.

4.6 Indirect Standard Model Tests via Precision Measurements

Evidence for new physics can also be provided by indirect searches. Proposed extensions to the Standard Model predict small but measurable symmetry deviations which may be the first hints for physics beyond the SM. Thus high precision measurements of Standard Model observables or searches for phenomena forbidden or suppressed in the Standard Model are sensitive to new physics. Although direct searches are easier to interpret, these indirect signatures for new physics can probe multi-TeV energy scales not easily reached even at the LHC and the proposed ILC.

Tests of the Vector-Axial structure of the Weak Interaction

The Standard Model describes weak interactions in terms of left handed Vector-Axial (V-A) currents. However, in the most general case, right-or left-handed Scalar, Vector, Pseudo-scalar, Axial-vector or Tensor interactions could be allowed. The observation of non V-A interactions, or right handed currents, would be evidence for new physics beyond the Standard Model. The current data cannot rule out the presence of non V-A terms at about the 10% level.

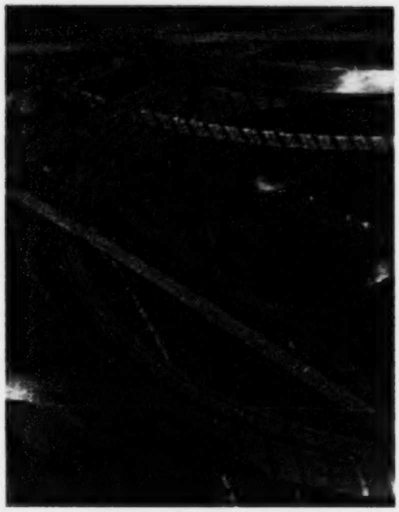
There are numerous complementary methods to test the V-A structure of weak interactions. At high energies, experiments at LEP have measured the Michel parameters which describe the weak decay of the tau lepton. At low-energies, tests include a precision measurement of the Michel parameters in polarized muon decay in the TWIST experiment at TRIUMF. This purely leptonic search is very clean and will lead to some of the most stringent constraints on the V-A form. However, the couplings and mixings in right-handed interactions could be such that neutron and nuclear β-decay searches are particularly sensitive. To that end, the TRINAT program at ISAC is studying the nuclear β-decays of ^{38m}K, ^{37}K, and ^{80}Rb atoms. They are also studying the β-ν angular correlation to place constraints on possible scalar bosons coupling to first generation quarks that are favoured in some non-standard Higgs models. Finally, the $\pi \rightarrow e\nu$ branching ratio is very sensitive to any scalar couplings of new particles which avoid the helicity suppression of the dominant axial coupling. The 0.1% precision measurement of this ratio underway at TRIUMF would, for example, probe mass scales for leptoquarks in the 200 TeV region.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Figure 3: The Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix governing weak quark couplings.

***CKM* Matrix Studies**

The CKM matrix (Figure 3) describes the degree of mixing in the quark sector. The elements of this matrix are the weak coupling strengths between quarks. The elements are complex, but unitarity constraints limit the 3-generation case to three real mixing angles and a complex *CP*-violating phase.



Superconducting cables used in particle physics applications; superconducting cable allows electrical currents to flow without resistance.

CP was first shown to be an imperfect symmetry of nature using kaons in 1964. For 30 years, no other cases of *CP* violation were observed until BaBar recently established that *CP* is also violated in *B* mesons. This was observed by comparing B^0 and $\bar{B}^0$ decays to the final state J/ψ K_s and related modes. The CDF experiment at the Tevatron followed with the observation of B_s meson mixing, providing significant additional constraints on the CKM matrix elements.

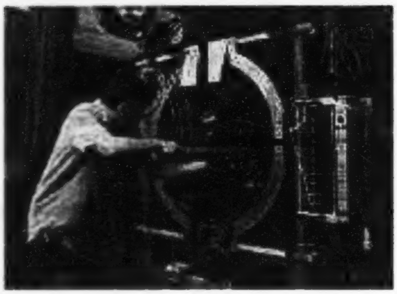
The elements of the CKM matrix must be determined by measurements of decay rates, branching ratios, and masses, and these experiments must be made in a variety of ways to access all quark couplings. A focus of the heavy flavour program is to undertake sufficient measurements to over-constrain the parameters of the CKM matrix, providing a sensitive test of the SM and possibly indicating new physics that would be directly observable at the LHC or elsewhere.

Nuclear physics experiments establish V_{ud}, by far the most precisely measured CKM matrix element, through studies of superallowed $0^+ \rightarrow 0^+$ β-decay transitions. The Canadian Penning Trap at Argonne National Laboratory has contributed to this program through high-precision mass measurements, while the 8π Spectrometer and 4π β-counting facility at ISAC have made high-precision branching ratio and lifetime measurements for the heavy superallowed emitters ^{62}Ga and ^{74}Rb. With the operation of the new TITAN facility, ISAC will be uniquely positioned to measure all three required quantities (decay rates, branching ratios, and masses) and will add several new precision cases to the world superallowed data. The V_{ud} matrix element is also accessed by measurements of neutron β-decay using cold neutrons.

One important feature of the superallowed β-decay program is the strong collaboration with the nuclear theory community to evaluate the radiative and isospin dependent corrections to the experimental values. Canadian work on superallowed β-decay is a good example of how close collaboration between theory and experiment can establish precision results of broad impact in subatomic physics.

Parity Violation Studies

Canadian scientists are also involved in high-precision measurements of parity violation (PV) symmetries in hadronic, leptonic, and atomic systems. These aim to search for weak interaction structure beyond the Standard Model via precise measurements of the energy dependence (running) of the weak mixing angle $\sin^2\theta_W$ at low energies. Experiments anticipated during the next few years could test Standard Model predictions up to the 25σ level. The experiments are sensitive to different electroweak radiative corrections, and so provide complementary tests to those at TeV mass scales. At JLab, Canadians play a major role in the *Q*weak experiment, which is a precision measurement of the proton "weak charge", $Q^p_{weak} = 1 - 4\sin^2\theta_W$. The experiment will provide the first high-precision measurement of the proton's weak charge with an accuracy of 0.3% on $\sin^2\theta_W$. A complementary program with Canadian collaborators will access $\sin^2\theta_W$ through a precision measurement of the weak charge of the electron, and will run at JLab following the anticipated 12 GeV upgrade later this decade. The running of $\sin^2\theta_W$ can also be investigated using atomic parity violating processes. Experiments planned for ISAC will use isotopes of francium which are well understood theoretically and have strong parity violating amplitudes.



Inserting a source into the Crystal Ball detector for energy calibration. Crystal Ball is operated in Mainz, Germany by a collaboration including physicists from Mount Allison University.

Electric Dipole Measurements

Permanent electric dipole moments (EDM) change sign under both the parity and time-reversal operations and, for an elementary particle, atom, or molecule, can only arise from polarization of the system by T-violating, or equivalently *CP*-violating, interactions. A non-zero measurement would be evidence for a new *CP*-violating interaction. New sources of *CP*-violation are required to explain the observed cosmic asymmetry between matter and antimatter and all currently favoured extensions to the Standard Model generically include *CP*-violating phases that induce sizeable particle EDMs. Present limits for the electron, neutron, and ^{199}Hg atom have already excluded significant fractions of parameter space for these models, and significant improvements over current EDM limits would have profound implications for the spectrum of viable extensions to the Standard Model and, ultimately, *CP*-violation.

Nuclei with collective octopole deformations enhance the atomic EDM induced by an underlying *CP*-violating interaction, and are expected to be strongest for A $\sim$ 225 nuclei. The most intense beams of such nuclei will uniquely become available at ISAC with the implementation of an actinide production target, providing an opportunity to significantly improve particle EDM

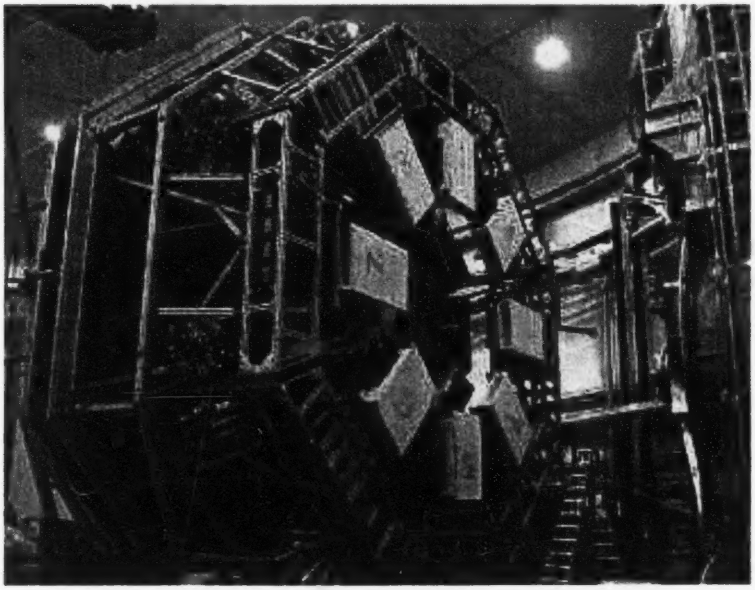
limits. An experiment planned for ^{223}Rn aims to improve current limits on non-flavour changing *CP*-violation by an order of magnitude. This will lead either to the detection of a non-zero particle EDM, or severely constrain *CP*-violation responsible for baryogenesis in the early Universe.

4.7 Quantum Chromodynamics

Quantum Chromodynamics (QCD) is the theoretical framework used to describe the interactions of quarks and gluons. At high energies the strength of the strong force is sufficiently weak that perturbative QCD calculations are possible. The predictions of QCD in this realm have been tested extensively. Experiments studying quark-scattering interactions at high energies find good agreement with QCD calculations. At lower energies QCD is not easily calculable, and in this regime predictions rely on effective models and computational techniques like lattice QCD. Great progress is being made in this area, leading to robust predictions of quark confinement and an understanding of the observed hadron spectrum. The following sections provide details on the research programs in these two regimes of QCD.

Studies in the Perturbative Regime

The strong coupling constant α_s has been measured at LEP, the Tevatron and HERA at various energy scales, confirming the "running of α_s", i.e. that the strength of the strong interactions decreases as the momentum transfer increases, thereby validating the perturbative-QCD picture. Tevatron and HERA experiments have tested QCD to high precision in various domains, in particular through cross section measurements of jets emerging at high



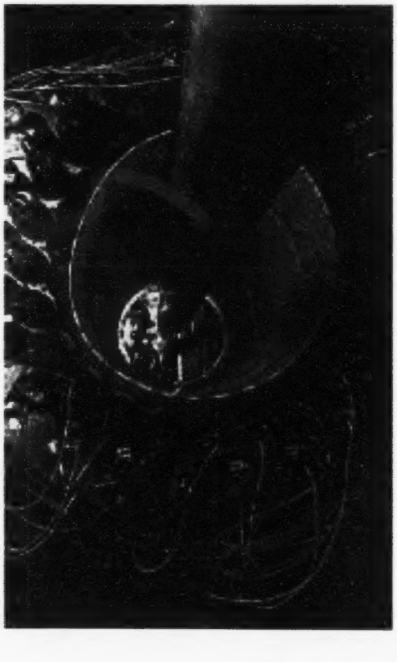
The G0 experiment in Jefferson Lab Hall-C, which probes the strange quark content of the proton. The mounting structure and 75% of the detectors for the G0 backwards angle detectors shown here were designed by Canadian physicists and built at TRIUMF.

transverse momentum, implying collisions at short distances. Deviations of these measurements from Standard Model expectations could be a signature of new physics. Multiple-jet final states may also be an indicator of new physics, as heavy objects can decay to jets, and these measurements provide a stringent test for higher order QCD calculations. Measurements of multi-jet final states will be some of the first contributions from the ATLAS experiment, which will extend them to energies far beyond those studied at the Tevatron and HERA colliders.

The physics of the bottom quark has a special role in QCD. In regions where α_s is not small, quantitative predictions of QCD are difficult. The mass of the bottom quark is large enough to overcome this difficulty but still small enough to make production at the Tevatron copious. Measurements at the Tevatron and HERA have yielded bottom quark cross-sections larger than theoretical predictions, which in turn has prompted renewed efforts in theoretical calculations to understand the source of the discrepancy.

The primary focus of Canadian researchers on the ZEUS experiment at HERA has been the description of the composition of the proton (structure function). HERA has extended the range in Q^2 (square of the momentum transfer of the exchanged boson), and x (fractional momentum of the struck quark), spanning nearly 6 decades in both variables. The combined electroweak and QCD fits at HERA have yielded structure function measurements with a precision of the order of 1-2% in the low x region. W charge asymmetry measurements at the Tevatron have constrained the d quark to u quark ratio in the region of high x where data from other experiments are scant. Enhanced data sets from HERA and from the JLab upgrade will help resolve remaining uncertainties in our knowledge of structure functions at large x. Extrapolations of the structure functions to the LHC kinematic range form the basis for cross section predictions at the LHC.

A worker peering down the electron beam pipe at Jefferson National Laboratory, where many Canadian subatomic physicists perform experiments.



Studies in the Non-perturbative Regime

As mentioned earlier, a quantitative understanding of confinement remains an outstanding problem of QCD. A key issue is the question of hadron structure. Can the properties of the nucleon such as mass, spin, polarizabilities, charge, and current distributions, be understood quantitatively in terms of the underlying quarks and gluons within the framework of QCD? Considerable progress has recently been made on the theoretical front to address this problem. The basic symmetries of QCD, primarily chiral symmetry, have been exploited to develop "effective field theories" capable of producing specific predictions of hadron structure and interactions at low energies (e.g. nucleon electric and magnetic polarizabilities and pion-nucleon interactions). Recent analytical and computational advances have allowed better calculations, which are then applied to the light quark sector with greater authority. The High Precision QCD (HPQCD) collaboration, with Canadian, US, and British theorists, has played a leading role in these improved calculations.

Canadian experimentalists are actively involved in a number of studies of hadron structure and dynamics using electromagnetic probes. An example is the study of the π^+ meson, one of the simplest hadronic systems whose form factor (F_π) is calculable in perturbative QCD. However, the details of the transition from the perturbative to non-perturbative regime are unknown. Because of the pion's small number of valence quarks, this transition is expected to be more easily observable than in any other system, and hence the measurement of F_π can provide an important test of our understanding of QCD in bound systems. Studies to gain insight into QCD-based models of hadron structure are also in progress. The *G*0 experiment, currently underway at JLab, will quantify the contribution of the strange-quark sea to proton structure by measuring the strange electric and magnetic form factors of the proton, assisting our understanding of the virtual squark contributions to the proton mass and spin. Early results indicate the strange-quark contribution to proton structure is small but nonzero.

QCD predicts a variety of exotic bound states where gluons can contribute to the quantum states of particles, or even form particles of pure glue. The former are called hybrids, and the latter, glueballs. An active area of investigation at BaBar and elsewhere is the search for new heavy hadrons, as a test of QCD models that can predict the spectrum of such resonances. There are exciting hints that some of these may be hybrids (quark anti-quark gluon) or diquark anti-diquark combinations. Hybrid mesons can be thought of as bound states in which the gluon is a constituent. An attractive alternative picture is one in which a "gluonic flux tube" forms between the $q\bar{q}$ pair in a meson, leading to a colour-force that is constant as the distance between the quarks varies. Recent lattice QCD calculations support this notion of the formation of flux tubes and their behavior with increasing quark distance, thus further emphasizing the non-trivial role of glue in QCD in the confinement region. A key part of the JLab 12 GeV experimental program is the GlueX experiment. The scientific objectives of GlueX are to identify the existence of exotic hybrid mesons by determining their unique J^{PC} quantum numbers, to measure their masses and decay channels, and to map out the spectrum of these particles.

Over the past few years, Canadian theorists have made considerable contributions to the field of hadron spectroscopy. They have contributed to an understanding of flavour properties and *CP* violation in the *B* sector, to the interpretation and diagnostic tests of some unusual new mesons discovered in recent years, and have been instrumental in mapping out new methods for handling the very difficult calculations associated with Quantum Electrodynamics and Quantum Chromodynamics.

In summary, while QCD is now firmly established as the fundamental theory of strong interactions, our understanding is lacking on several critical fronts. The modeling techniques of former decades have been replaced by rigorous theoretical methods of effective field theories and lattice QCD. This, in combination with precise data, is expected to initiate a revolution in our understanding of QCD.

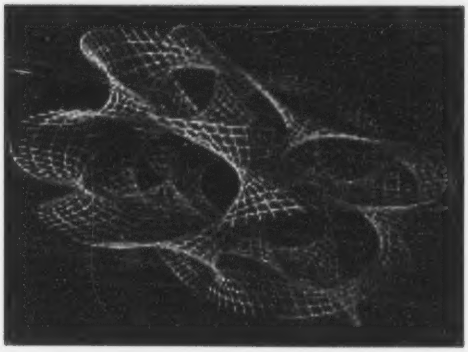
4.8 Cosmological Implications: Dark Matter Searches and String Theory

Conventional matter in the Universe is well described by QCD in the framework of the Standard Model. However, it is now known that the bulk of the matter of the Universe is unconventional and completely unknown to us. The world wide community of subatomic physicists, cosmologists and astronomers considers the questions of dark matter and dark energy to be of the highest priority.

On the theoretical front a growing area of research which bridges string theory, cosmology and phenomenology aims to elucidate this deep mystery. Canada hosts a growing number of highly-regarded theorists in this emerging field of superstring cosmology. The new theory of the early Universe which emerges provides a possible explanation for why we live in exactly three large space dimensions. Recent work also provides a new explanation for the observed large-scale distribution of matter in the Universe.

The search for direct evidence for dark matter is a major experimental effort world wide. The favoured candidates for dark matter are Weakly Interacting Massive Particles (WIMPs). These particles are manifest in supersymmetric models, and might be detected by measuring the recoils of normal matter following scattering of WIMPs. Event rates are expected to be at levels as low as

A computer simulation of multi-dimensional spacetime.



a few events per year per tonne of target material. Experiments planned for SNOLab will play a major role here. The key to these experiments is the control of radioactive backgrounds, and with its great depth and clean construction SNOLab will be the best location in the world. It is not known whether WIMP interactions with conventional matter will proceed through spin-dependent or spin-independent interactions; different target materials are required to allow for both options.

A vigorous research program at SNOLab is planned, and initial approval for the installation of SuperCDMS, PICASSO and a DEAP prototype has been granted. CDMS is a mature experiment that will continue to lead the world for the next few years. Scaling to a much larger detector size is not feasible for CDMS, and new technologies are required in both spin-dependent and spin-independent modes. Two Canadian projects are particularly interesting in that regard. The PICASSO detector has a unique technology that allows it to search for spin-dependent interactions using liquid droplet detectors. The latest results from PICASSO set the world's best limits on WIMP interaction rates for some of the allowed WIMP mass range. PICASSO is now installing a larger detector with increased sensitivity that will set the world's best spin-dependent limits and begin to challenge theoretical predictions for the WIMP interaction rates. Another exciting Canadian project, currently in the R&D phase, is the DEAP project which intends to utilize liquid argon as a spin-independent dark matter target. The strength of this technique is the ability to use the pulse-shape discrimination available in argon to deal with the low-level residual background radiation. A 10 kg prototype is currently under construction for early installation at SNOLab. The technique will allow a very cost effective scale-up in size to a 1000 kg detector.

The abundance of dark matter can be explained in cosmological models of the big bang provided dark matter particle masses are well below the TeV scale; if so, they could be produced in terrestrial accelerators like the LHC in the coming decade. One particularly promising WIMP candidate is the lightest supersymmetric particle. Searches for supersymmetry and dark matter candidates are amongst the principal objectives of the ATLAS program. The challenge will be to map out the decay chains that lead to the lightest supersymmetry candidate, allowing those candidates that are consistent with dark matter to be distinguished from those that are not.

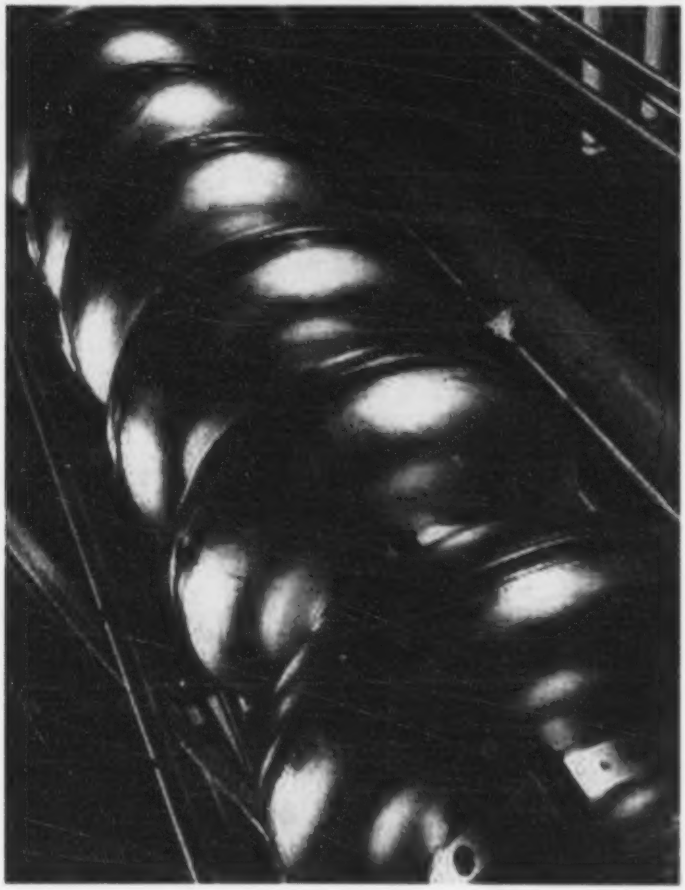
Dark matter may also be observed indirectly. WIMPs that scatter in massive bodies like the Earth or Sun may become gravitationally bound. Over time, they might become sufficiently numerous that their annihilation products could be observed in gamma ray telescopes such as VERITAS.

Input from all of these measurements will help to elucidate the nature of dark matter and supersymmetry. With participation in the complementary programs at ATLAS, SNOLab and VERITAS, Canada is well positioned to be a leader in the search for dark matter and supersymmetry. The potential synergy between cosmological observations and terrestrial production of dark matter particles is a tantalising possibility. Discoveries of this nature would be breakthroughs of monumental proportions.

4.9 Outlook

The impending turn-on of the LHC is a source of much excitement within subatomic physics, as the answers to fundamental questions which have remained unanswered for decades may soon be within reach. These include the origin of the mass of the fundamental particles, and the nature of future extensions of the Standard Model such as supersymmetry or extra large dimensions. Many of the new particles predicted by these theories are expected to be within reach of the LHC, and Canadian scientists participating at ATLAS eagerly look forward to the first results.

In addition to the searches for the Higgs and physics beyond the Standard Model, ATLAS will perform many other measurements. These include probing QCD at new energy scales, measurements of rare heavy quark processes and CKM physics, precision Standard Model tests such as W-mass and triple gauge boson coupling measurements, exploring a new frontier of relativistic heavy ion physics, and many more. The breadth of physics that will be performed by ATLAS is a strong motivating factor driving the diverse faculty and scientist membership of the project in Canada.



Superconducting accelerator structures made of niobium, developed for research towards a future linear collider.

The search for dark matter is an example of the synergies both within subatomic physics and with other fields. The evidence for dark matter is at present astrophysical in origin and largely indirect. The direct detection of the particles which make up this matter would be a tremendous contribution from subatomic physics to our knowledge of the Universe as a whole. One of the keys to this experimental program is a lab with low and well-understood backgrounds, and SNOLab will be the best location in the world for these experiments. Dark matter may also be observed indirectly with high energy gamma ray telescopes, such as VERITAS. The results from both of these programs, together with the complementary search for supersymmetry at ATLAS, will help elucidate the nature of this profound mystery.

The elusive neutrino has been a constant source of surprises. Building on the success of the Sudbury Neutrino Observatory, a rich program in neutrino physics is planned. The T2K long baseline neutrino oscillation experiment is under construction to investigate mixing, and possibly *CP* violation, in the neutrino sector. Experiments in neutrinoless double beta decay at SNOLab have been proposed that would have the sensitivity to measure absolute neutrino masses and determine their Dirac or Majorana nature. If history serves as a useful guide, many new discoveries can be expected from studies of neutrinos.

The groundwork for the exploitation of the physics at the TRIUMF ISAC facility has been laid and is starting to bear fruit. The ISAC facility is the world's premier radioactive beams facility, and real advances will stem from these newly available beams in nuclear astrophysics and nuclear structure studies. A complete program of Standard Model tests and searches for physics beyond the Standard Model using exotic nuclei is also underway or being prepared at ISAC.

Theorists in Canada have made important contributions to our understanding of subatomic physics. Canada's theorists have an international reputation, with an excellent track record both for producing cutting edge research and for training students, many of whom have gone on to prominent positions around the world. Many of these theorists are already pursuing ideas that will be tested by the next generation of experiments discussed in this section. They will continue to work at the cutting edge of subatomic theory covering the breadth of nuclear and particle physics research.

The future of physics at the energy frontier after the LHC will be the International Linear Collider (ILC), which will make a significant impact on charting the Big Bang time-line. If one or more Higgs, supersymmetric particles, or WIMPs are discovered at the LHC, then the ILC will investigate the details of production – the masses, the interactions of the particles, why the Higgs particles even exist – as well as shed light on dark matter and probe new particles and new symmetries. Canadians are well placed to be leaders in the exciting physics program that will unfold over the next 5 to 10 years. Just as we have invested in SNO, ISAC, and ATLAS over the last 10 years to prepare for the current round of experiments, we must invest in ILC detector and machine R&D over the next five years to be full participants in energy frontier physics over the next decade and beyond.

5 The Economic Impact of Subatomic Physics

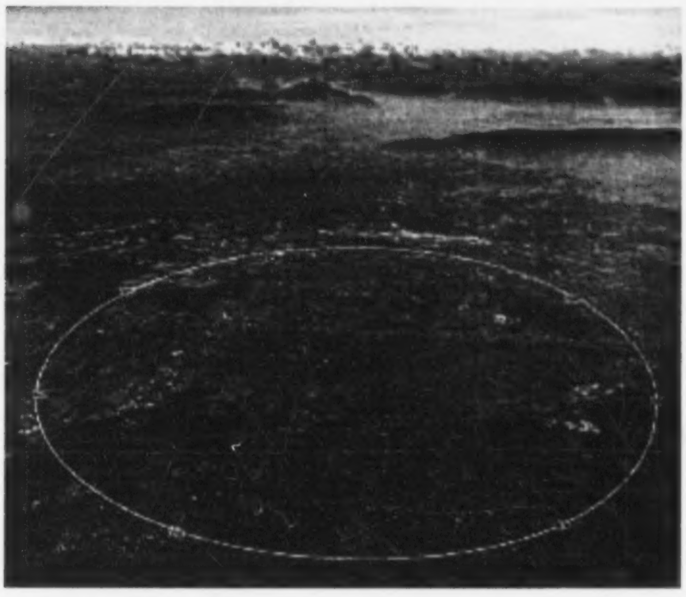
Canada's economy is undergoing significant change as it transitions from being resource-based to being knowledge-based. It is critical for Canada to have a strong and vibrant scientific community, to provide expertise and highly qualified people to Canadian industry. Furthermore, today's basic research leads to tomorrow's technologies, which will be critical to Canada's future competitiveness. In particular, Canada must remain at the forefront of subatomic physics research. This research pushes the frontiers of human knowledge, and in doing so, lays the foundations for new technologies in the physical and life sciences, changing the way we travel, communicate, and work. The economic impacts of subatomic physics are many, and include not only the technological benefits of research in the field, but also the highly qualified personnel who benefit society in myriad and often unpredictable ways. This section summarizes the economic benefits of research in subatomic physics.

5.1 Technological Impact

Modern experiments in subatomic physics are challenging and typically require innovations to make a measurement possible which was previously only imagined. For example, the goal of an experiment may be to measure the rare decay of a subatomic particle or nuclear isotope, in order to challenge a prevailing theory. Such an experiment may require a novel way to suppress background sources, or a detector of unprecedented resolution in order to isolate a single event of

interest from a multitude of candidate events. As a result of such science-driven demands, experiments in subatomic physics drive detector and electronics technology, and these innovations often lead to new technologies of benefit to society.

Quantifying the indirect but very large impacts of subatomic physics instrumentation to society is often difficult. As stated by Rosenberg[3], instrumentation flow is "particularly strong from physics to chemistry, as well as from physics and chemistry to biology, clinical medicine and ultimately to health-care delivery." A good example of such technology transfer is provided by the accelerators invented to facilitate the study of subatomic particle interactions. Although originally designed for basic research, accelerators are now used worldwide for such diverse applications as cancer therapy, studying the structure of viruses, designing new drugs, and the fabrication of semiconductors and microchips. A specific case is the recently-completed Canadian Light Source, in Saskatoon, whose roots lie in subatomic physics, but whose intended applications lie in many other fields, both basic and applied. Other examples of important spin-offs from subatomic physics research include nuclear medicine and medical diagnostic tools such as MRI. The World Wide Web is another example of a spin-off from subatomic physics research. The WWW was developed at CERN to enable high energy physicists to work together more efficiently, specifically because of the widely and internationally co-operative nature of subatomic physics. At the time of its invention, it was completely unforeseen that the WWW would revolutionize the way we communicate, teach and do business, but today its effect on society is undeniable – it is often our first source for news, entertainment, and information.



An aerial view of the CERN site near Geneva, Switzerland. The white circle marks the LHC tunnel, which is approximately 50m below the surface.

[3] See Section 9.2 for studies relating to this section of the report.

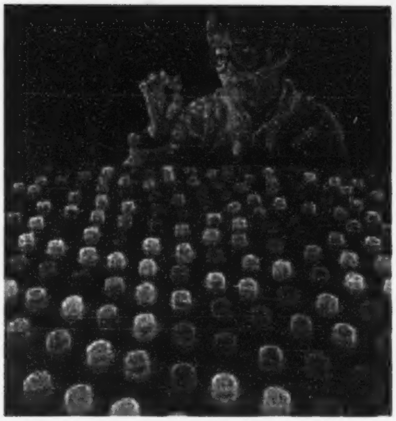
In spite of its benefits, basic research is vulnerable. It is a risky activity that seeks scientific knowledge for its own sake, and neither its outcome nor its applications can be predicted. Even great scientists have sometimes been unable to foresee the relevant applications of their work. Ernest Rutherford, discoverer of the atomic nucleus through his research in part at McGill University, said in 1933, "Anyone who expects a source of power from the transformation of the atom is talking moonshine." Today, nuclear power is an industry in which Canada is a world-leader, and is gaining greater attention given the Kyoto Protocol intended to limit greenhouse emissions.

Economists have studied the economic impact of the innovations derived from research, and have estimated that one-half to two-thirds of the economic growth of developed nations is knowledge-based. Recent studies have estimated that the average annual rate of return on investment in basic research ranges from 28% to 50%, depending on the assumptions used. There is direct evidence that past investment in subatomic physics research has paid for itself many times over.

What follows are ongoing examples of Canadian R&D in subatomic physics technology which have applications in other fields.

Silicon Photomultiplier: Conventional photomulitipliers have their roots in subatomic physics experimentation and are the most widespread vacuum electronic device today, comprising an industry with billions of dollars of annual revenues worldwide. Their development is now driven by medical imaging requirements, but they are used in a wide range of disciplines including space research, archeology, geology, physics, biology, astronomy, metallurgy, chemistry, and agriculture. The silicon photomultiplier (SiPM) is a new development of this device using a novel photosensor based on solid state technology, being developed for use in subatomic physics experiments; Canada is playing a leading role in this development through our participation in the GlueX and T2K projects. SiPMs have a number of favorable characteristics, such as insensitivity to high magnetic fields, compactness, radiation hardness, cost effectiveness, good gain and superior energy and timing resolution. These attributes make SiPMs suitable not only for subatomic physics applications, but also highly desirable for medical physics applications, such as positron emission tomography (PET), which would benefit from the enormously increased spatial resolution they offer, and lead to the earlier diagnosis and prevention of diseases.

Micro-Pattern Gas Detector: One of the most promising innovations in radiation imaging today is the development of charged particle detectors in which ionization electrons are tracked using micro-pattern gas detectors (MPGDs). The development of MPGDs is driven by the requirements of basic subatomic physics research and makes use of recent advancements in simulation software, modern readout electronic design, and surface manufacturing. MPGDs will be at the center of tracking technology in future particle physics applications such as T2K, SNOLab, and the ILC, and in other high precision detectors. The development of novel particle detectors has numerous applications beyond pure physics research, particularly in the areas of medical and industrial imaging.


Plastic scintillator detectors used at Fermilab.

Noble Liquid Calorimeter: Noble liquids (neon, argon, krypton, xenon) are widely used as detection media in particle physics calorimeters; a recent example is the ATLAS liquid argon calorimeter. A measurement of ionization electrons as well as scintillation light provides a way of disentangling nuclear recoils from electron recoils, and is a key to the identification of dark matter candidates. Detecting the ionization electrons also improves the energy resolution, but more importantly, it allows a measurement of the gamma interaction point with high precision. This feature is again especially relevant for positron emission tomography, which would highly benefit from improvement in energy and position resolution.

High Performance Computing: Subatomic physics has pushed the development of high performance computing, such as Grid computing and data mining. High energy physics experiments involve the collection of enormous amounts of data, and large-scale computing facilities are required for their analysis. The innovations expected from Grid computing will do for large-scale computing what the World Wide Web has done for information sharing. Canadian examples of Grid computing are WestGrid and GridXl, both of which have significant subatomic physics leadership.

Modelling and simulation research in subatomic physics will also result in longer-term benefits to society. For example, the development of new computing initiatives will benefit areas including the development of new pharmaceuticals and other custom-designed chemicals, improved data-mining techniques, and better modelling of geophysical systems and the environment.

A few examples of the direct industrial connections and spin-offs arising from subatomic physics research in Canada include:

Bubble Technology Industries: radiation and threat detection. BubbleTech is a Chalk River-based manufacturer of radiation dosimeters and radiation measurement instruments for customers in Health Physics and other areas who require radiation monitoring and protection.

MDS-Nordion: radio-isotope production. MDS-Nordion is a division of MDS Inc., a global health and life sciences company specializing in radioisotope production and radiation related technologies. Under a 28-year ongoing partnership with TRIUMF (which won the NSERC 2004 Synergy Award for Innovation), TRIUMF operates three high intensity cyclotrons for Nordion at the TRIUMF site. From this facility, Nordion produces medical imaging tracers for an estimated 45,000 patients worldwide every week. MDS-Nordion in Vancouver has ~50 staff dedicated to isotope processing and supports 35 TRIUMF staff members to operate the cyclotrons. The partnership has contributed to TRIUMF's stature as a premier international scientific institution and to MDS Nordion's emergence as the world's leading supplier of diagnostic imaging and therapeutic isotopes.

D-PACE: particle accelerator engineering. D-PACE is a TRIUMF spin-off company providing state-of-the-art engineering services to the particle accelerator industry, specializing in beamline systems design (ion sources,beam transport simulation, etc.), diagnostics and magnets. The company licenses technology from TRIUMF for sales to the international market, and was founded by Dr. M. Dehnel, who obtained his Ph.D. for research at TRIUMF in 1995.

JML Biopharm: medical tracers. JML Biopharm is a Vancouver company started by a TRIUMF research associate in 2001; it currently employs 5 staff members and specializes in customized labellings of molecules for the drug manufacturing industry and for medical imaging.

5.2 Training of Highly Qualified Personnel

Subatomic Physics is an excellent training ground for Highly Qualified Personnel (HQP). Students are attracted to subatomic physics by the exciting research opportunities there. While working on fundamental subatomic physics questions, they are exposed to many of the latest technological and computing innovations. In addition, graduate students in subatomic physics often benefit from their involvement in international collaborations; this international experience is of great benefit to them as they move into a globalized economy.

Many students find permanent positions in the field and contribute to long term research progress in subatomic physics. However, the majority of our highly qualified personnel move on to rewarding positions in other sectors. There is a growing realization that the transfer of capabilities, modes of thought, and knowledge to all parts of the economy through graduate student training may be at least as important as the direct transfer of information by more formal routes, and that this value may have little to do directly with the student's specific field of study. It is rather difficult to quantify the magnitude of this benefit. However, there is no doubt that the students who find jobs in the broader economy provide important economic impact to Canada through their fruitful collaboration with industry and their positive impact on other fields of science.

A subatomic physics graduate student working on the 8pi Gamma-Ray Spectrometer at TRIUMF's ISAC facility.

Ultimately, the value of a physics education to society is reflected in the high salaries and the very low unemployment rate enjoyed by those holding advanced degrees in physics. A study of 945 Canadian physics graduates found the unemployment rate of Canadians trained in physics to be less than 1%. This study also found that of those who were employed, M.Sc. and Ph.D. graduates from subatomic physics programs commanded salaries that were on average 25% higher than those with advanced degrees in other branches of physics – a direct measure of the value that the private sector places on their skills and education. The following two quotes, from Canadian businesses in the technology sector, highlight this value:

> Today, much training is going to be obsolete during a technology career, except for the foundation sciences: physics, mathematics and chemistry. The foundation sciences, and physics in particular, give people the ability to get into any emerging field. This is the reason physicists are so successful in highly technical positions. For example, at Creo, we grew our annual revenues from $10M to almost $1 billion by physics-based innovation. In Canada, we employ about 60 physicists, about half of them with advanced degrees.
> **– Dan Gelbart, founder and CEO of Creo (now a division of Kodak)**

> Bubble Technology Industries is a company that has benefited from the Subatomic Physics Training program in Canada. North America needs such physicists badly at this time and there is a serious shortage of them due to closures of nuclear physics departments over the last two decades. BTI is always looking for good candidates with subatomic physics training and we will continue to seek such physicists for the foreseeable future.
> **– Harry Ing, Bubble Technology Industries, Chalk River, Ontario.**

During the preparation of this report, we surveyed M.Sc. and Ph.D. graduates from the ATLAS, BaBar, CDF, OPAL, and ZEUS high energy physics projects. Of those in permanent positions (160 former graduate students), 21% had found posts in academia, 33% as staff scientists at research-based organizations, and the remainder in industrial or non-traditional positions. The non-traditional positions included fields as diverse as government agencies (such as CSIS and the NRC), finance, public education, and science journalism. In the technology and industrial sectors, subatomic physics graduates held positions in companies in such areas as computer software, electronics, geographical information systems, nuclear energy, and medical physics.

Thus, subatomic physics graduates are sought-after and their training enables them to make contributions to a wide range of public and private organizations. **An investment in subatomic physics HQP is an investment in a technologically innovative economy.**

The following quotes about the usefulness of SAP training come from recent subatomic physics graduates and are reprinted with their permission:

> My training in experimental subatomic physics has provided me with the technical and communication skills necessary to succeed in a high-tech engineering environment. I have found the "first principles" problem-solving approach learned in physics to be different yet complementary to the approach of most engineers. The experience I have gained while developing new detectors and experimental apparatus for subatomic physics experiments has provided me with a familiarity towards pushing the limits of existing technology. This experience has been quite useful in an industrial R&D setting.
> **– Andrew Feltham, Ph.D. (University of British Columbia, 1992)**
> **Senior Staff Software Engineer, Broadcom Canada Ltd**

> I'm currently employed as a physicist by a company in the pulp and paper sector. I run a sampling lab, and my job consists of running experiments to determine if our sensors can be used to measure our customer's product properties to the desired level of accuracy. The job requires a detailed understanding of the lab equipment – the physical principles of operation as well as the limitations of each sensor. We use nuclear and X-ray gauges with a variety of radionuclides and energies, and also have a range of infrared and visible light spectrometers, all of which can be customized to a certain degree. Designing the experiments and configuring the equipment requires a clear idea of the questions that need answering and the tradeoffs that can be made, and analyzing the results of the experiments requires a good grasp of statistics. Then, documenting the results in a way that our customers, salespeople, manufacturing personnel, and field service engineers can understand calls for good communication skills and an ability to simplify explanations without losing the "science". These are all skills that I learned during my Ph.D. and postdoctoral studies in experimental high energy physics.
> **– Reena Meijer-Drees, Ph.D. (University of British Columbia, 1991)**
> **Principal Research Scientist, Honeywell**

My training in particle physics has prepared me for my finance career in several ways. Firstly, it gave me a firm grounding in Monte Carlo techniques which I have used extensively in modelling complex financial instruments. Secondly, the process of obtaining a physics Ph.D. is itself a valuable discipline to learn. Doing a Ph.D. means having a large, complex problem the solution of which cannot immediately be seen. The patience, persistence and detachment necessary to complete the thesis research are skills that translate very readily to the business world. Finally, working in large international physics collaborations taught me valuable communication and group interaction skills that are absolutely critical for success in a large financial institution.
– LeeAnn Janissen, Ph.D. (Carleton University, 1993)
Vice President & Director, TD Securities

I owe much to my training in subatomic physics. Everything I do could be classified as systems development. Subatomic physics exposes one to a large variety of systems: from the physics systems, through the technical systems of a detector and beyond, through the "systems" coordinating all the people involved. In subatomic physics one has many, many opportunities to see how successful scientists understand a system at various levels of abstractions, from black box all the way down to root cause when required. The Blue Gene/L supercomputer is a nice demonstration of the value of training in subatomic physics. The BG/L machine itself is a descendant of Lattice QCD (LQCD) machines. The two main proponents of BG/L have subatomic physics backgrounds.
– Burkard Steinmacher-Burow, Ph.D. (University of Toronto, 1994)
Development Engineer, IBM

When I tell people that I am in journalism and that I used to study physics, I always get the same response of "that's a big change." Now I don't particularly agree with that because I find the two are, in many ways, quite similar. When you study physics, you learn how to use math as a tool to understand/explain the world around you. When you study English and/or journalism, you learn how to use the English language as a tool to understand/explain the world. So basically, all I feel I've done is switched my training from math to English but I still essentially do science explaining/understanding. While I might not directly use the skills that I learned, I find the biggest difference between me and the other journalists with different backgrounds is that I am not afraid of these subjects. Most journalists come from a liberal arts background and do not understand the difference between a quirk and a quark. I studied quarks (b quarks specifically). Particle physics is very rigorous and this has given me quite a good understanding of how to evaluate the scientific validity and importance of research – two things that are incredibly handy and important to a scientific journalist.
– Zerah Lurie, M.Sc. (University of British Columbia, 2002)
Science Journalist, CBC Vancouver

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– Burkard Steinmacher-Burow, Ph.D. (University of Toronto, 1994)
Development Engineer, IBM

When I tell people that I am in journalism and that I used to study physics, I always get the same response of "that's a big change." Now I don't particularly agree with that because I find the two are, in many ways, quite similar. When you study physics, you learn how to use math as a tool to understand/explain the world around you. When you study English and/or journalism, you learn how to use the English language as a tool to understand/explain the world. So basically, all I feel I've done is switched my training from math to English but I still essentially do science explaining/understanding. While I might not directly use the skills that I learned, I find the biggest difference between me and the other journalists with different backgrounds is that I am not afraid of these subjects. Most journalists come from a liberal arts background and do not understand the difference between a quirk and a quark. I studied quarks (b quarks specifically). Particle physics is very rigorous and this has given me quite a good understanding of how to evaluate the scientific validity and importance of research – two things that are incredibly handy and important to a scientific journalist.
– Zerah Lurie, M.Sc. (University of British Columbia, 2002)
Science Journalist, CBC Vancouver

A youngster explores a Van der Graaf generator, which uses the same principles used in small particle accelerators.

Although the practice of law may not at first view seem related to the scientific skills learned during the course of my studies in physics, the analytical skills, rigorous problem solving training, attention to detail and ability to discern pattern and synthesize first principles from seemingly unrelated data which I learned during the course of my Ph. D. in subatomic physics have been invaluable in my practice as a lawyer. Not only have I benefited from this general intellectual training and methodology, but my physics background also allows me to more fully understand scientific or technical expert reports, intellectual property and information technology files, and gives me the necessary mathematic background to understand the financial expertise or actuarial models that are used in complex commercial or insurance matters, thereby giving me a clear edge in such files. I remember one case in particular where I was able to refine a detailed mathematical model submitted by our engineer in order to reflect the correct loss of profits based on the instantaneous fluctuations of a commodity, thereby reducing the claim by several million dollars, something which only my studies in physics could allow me to do. There is no doubt in my mind that my studies in physics makes me a better lawyer today.
– Patrick Girard, Ph.D. (McGill University, 2000)
LL.B. Stikeman-Elliott LLP

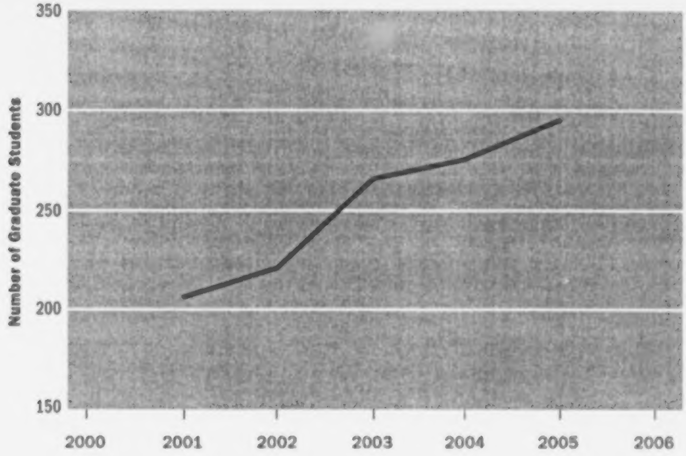

Figure 4: Number of students enrolled in experimental or theoretical subatomic physics graduate degree programs in Canada, for the years 2001-2005.

Over the past five years, the number of graduate students in subatomic physics programs at Canadian universities has steadily increased. As shown in Figure 4, the number of graduate students currently involved in subatomic physics research projects is approximately 55% higher than it was at the time of the previous long range plan in 2001. This increase is broad-based, with all experimental and theoretical fields of study in subatomic physics across Canada seeing strong growth. Upon graduation, many of these students will make valuable and significant contributions to Canada's future economic and social fabric. Since the practical implications of basic subatomic physics research often take unexpected forms, we can only state with certainty that the economic impact of their contributions will be positive, and will help Canada to remain a world technology leader.

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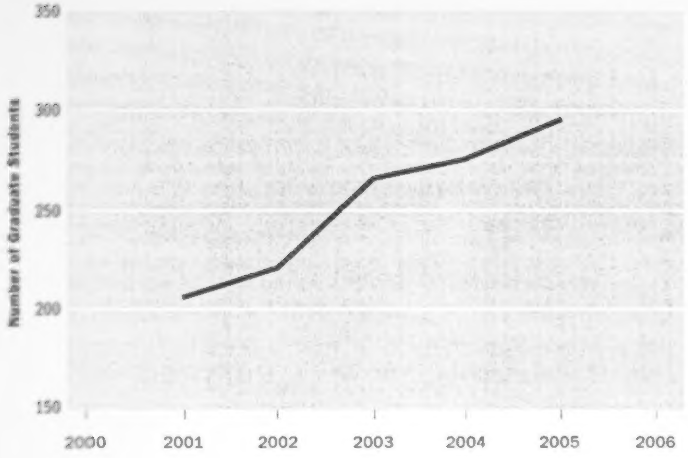

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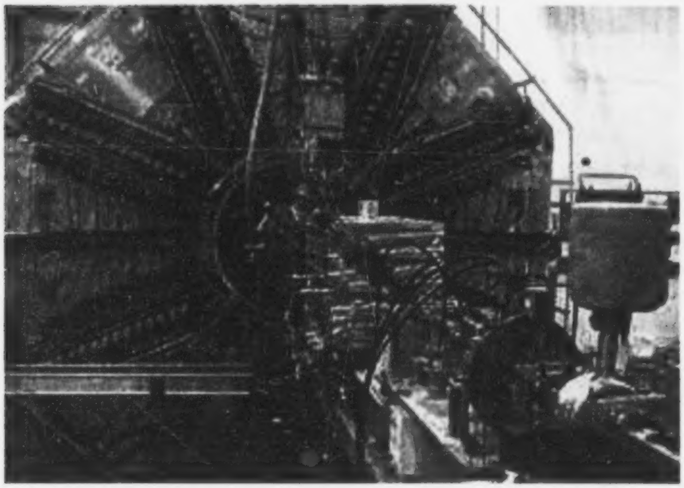
6
Support for Subatomic Physics in Canada

6.1 Overview

The Canadian subatomic physics community optimizes its research program through planning exercises like the current Long Range Plan (LRP). This community-driven exercise recommends a limited number of projects for concentrated effort, balancing scientific merit with potential impact, expertise, interest and available resources. The Natural Sciences and Engineering Research Council (NSERC) is usually the lead funding agency for these projects. However, some projects are supported by a variety of agencies or facilities and the funding scheme can be complex. Coordination of the different funding agencies and mechanisms is essential for the success of the field, and the LRP Committee has been asked to comment on the role of those agencies and institutes that contribute most significantly to subatomic physics in Canada.

Subatomic physics is conducted at a range of very different scales, both in size and time. An experimental program might involve a small group conducting a single experiment at an existing facility over a time scale of about a year, while another might involve a large international collaboration, continue for a decade or more, and require the construction and operation of very large detectors or facilities requiring hundreds or thousands of people.

Fortunately the experimental techniques, particle detector technology, electronics, computing and analysis facilities overlap considerably across all subatomic



The G0 experiment in Jefferson Lab Hall-C, which has significant Canadian contribution through the support of NSERC and TRIUMF. Visible in the figure are some of the 300 phototube bases built and tested at TRIUMF.

physics projects and it is possible to enhance the productivity of the community with a strong infrastructure base. Infrastructure provides facilities where experiments may be performed; highly skilled technical personnel to build, operate, and maintain the unique and complex instrumentation; and computing and networking infrastructure capable of handling the large data samples characteristic of subatomic physics.

It is clearly essential that the funding review mechanisms in Canada be treated together so that a coherent program including capital expenditures, infrastructure support and operating funds for experiments and facilities be maintained. In this context, a mechanism such as the proposed Major Science Investment Panel (MSIP) that gives coherent oversight to the many sources of funding would be very welcome.

6.2 Financial Support for Subatomic Physics

The funding mechanisms for subatomic physics in Canada are complex. Research personnel – faculty members, post-doctoral researchers, and students – are usually university based, and their research activities such as travel and equipment and supplies are funded through NSERC Discovery Grants. In recent years capital support has also come through the Canada Foundation for Innovation (CFI) in partnership with provincial programs. Subatomic physics has benefited from vigorous faculty renewal resulting in part from the Canada Research Chair (CRC) program. Both CRCs and regular faculty appointments bring new vision and directions to the Canadian subatomic physics community. Finally, the National Research Council (NRC) oversees the operation of the federally-funded TRIUMF national lab, which provides infrastructure support to the subatomic physics program.

To set the scale for the following discussion, we note that the annual budget for TRIUMF is currently of order \$45M, the subatomic physics share of NSERC is approximately \$23M per year, and over the past 5 years, the CFI has injected an average of about \$15M per year into subatomic physics infrastructure.

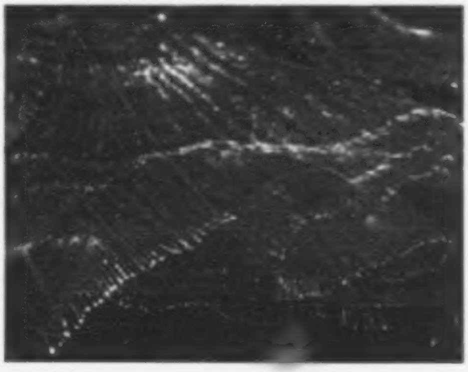
NSERC – Managing the GSC-19 Envelope

Subatomic physics experiments have financial requirements that vary greatly as they progress from construction to operational phases. The construction phase is characterized by large capital expenditures for materials, engineering infrastructure, and technical support, while the operational phase requires funding for research associates and students; computing facilities for data analysis; and travel or relocation to distant laboratories for detector operations and analysis work. Funding for theorists is primarily used to support the training of graduate students and research associates; a small fraction provides for infrastructure such as computing. Experimentalists and theorists require modest support for conference travel and advanced institutes, which are essential for dissemination of results and to keep abreast of developments in the field. NSERC is generally the source of funds for all these activities.

NSERC Discovery Grants are reviewed by Grant Selection Committees (GSCs). Subatomic physics (GSC-19) is unique within NSERC due to its use of an **envelope**, whereby a single budget is the source of all funds for equipment, infrastructure, and operations. All other GSCs, including other branches of the physics community, are given separate budgets for operating and equipment; infrastructure funding comes from a separate NSERC program. GSC-19's envelope allows funds to be shifted from equipment to operating as a major experiment comes on-line, and allows technical infrastructure to move from one project to another at different project phases. The envelope system has served SAP well over the last 15 years, allowing forward planning exercises to identify upcoming major capital needs and plan for them.

GSC-19 also administers the NSERC Major Facilities Access (MFA) program for subatomic physics infrastructure at universities. These grants play a particularly important role in the sharing of infrastructure costs across projects, as discussed in Section 6.3.

During the past 5 years, GSC-19 has benefited from small increments to the envelope based on a reallocations exercise and some compensation to account for new applicants. However, these increases have not kept up with the rate of inflation, and do not adequately account for the growth in the field and the need for capital spending on infrastructure.



High-tech cloth made of scintillating fibres, which emit light when charged particles pass through them.

The Canada Foundation for Innovation

The Government of Canada established the CFI as an independent, not-for-profit corporation to support the development of world-class research infrastructure in Canada. Infrastructure funded by CFI has been critical to the expansion of the subatomic physics program in Canada.

For example, the SNOLab facility, currently under construction at the site of the Sudbury Neutrino Observatory, was made possible through a $38M award from the CFI International Joint Venture fund. The CFI also provided funding to the Laboratory for Advanced Detector Development (LADD), which supports fundamental research into the development of detectors for subatomic physics and medical applications. The Tier 1 Computing Centre for ATLAS data analysis is being funded through a contribution from the CFI, as are other high performance computing centres in Canada that are shared among many disciplines including subatomic physics.

The CFI is also committed to supporting new researchers and Canada Research Chairs. Through these programs, new investigators in subatomic physics have been very successful at developing national and international research programs, and have used CFI-funded infrastructure as leverage to obtain significant operational support from the GSC-19 envelope.

CFI support has been of enormous benefit to the development of subatomic physics infrastructure. However, this infrastructure requires concomitant increases in operating funds, putting the GSC-19 envelope under considerable stress. The numerous new investigators, with very active research programs, look to NSERC for operational support. In addition, the source of operations support for facilities like SNOLab has not yet been identified. The current envelope simply cannot support these operating costs without serious damage to the entire subatomic physics research program in Canada. A more comprehensive approach to developing and funding large new facilities is clearly required. This was the goal of the proposed Major Science Investment Panel (MSIP), and we encourage the government to continue this process so that Canada will have a robust mechanism for building and managing leading-edge research facilities. In particular, subatomic physics – and Canadian science in general – need a mechanism that ensures that all large science initiatives have identified resources for both capital funding and operations from the outset.

6.3 Facilities, Institutes, and Other Infrastructure Support for Subatomic Physics

A healthy and sustainable subatomic physics programme requires a balance between detector R&D, experiment construction, experiment operations, and physics analysis. This requires trained engineers and technicians with the tools necessary to design and prototype detector elements, participate in the construction of major new pieces of subatomic physics experiments, and maintain these devices once they have been installed and begun to operate. In Canada, this infrastructure is provided in a number of ways. It may come through facilities like TRIUMF or SNOLab, through NSERC Major Facilities Access grants, or through organizations like the Institute of Particle Physics. This section describes the infrastructure support available to the subatomic physics community from a variety of sources.

A group of technicians from Alstom Canada (Levy, Quebec) with one of the quadrapoles designed at TRIUMF and built in Canada by Alstom for the LHC at CERN.

The TRIUMF Laboratory

The TRIUMF Laboratory is an accelerator complex near the UBC campus in Vancouver, funded by the federal government through the National Research Council and managed by a consortium of 13 Canadian Universities. It has been in operation for over 30 years, maintaining and operating accelerators to provide a variety of beams for subatomic physics experiments and interdisciplinary applications, including programs in condensed matter, chemistry, engineering and medicine. The TRIUMF ISAC facility (Isotope Separator and Accelerator Complex) attracts researchers from across Canada but also has an equal number of international users from Europe, Japan, and the US.

Much of TRIUMF's operations are in support of its on-site accelerators, including operation of the ISAC complex, work to develop and deliver new radioactive isotope beams, expansion of the ISAC accelerator complex to provide two independent accelerated radioactive beams, and the development of a second ISAC production station based on a new high intensity proton beamline. The high intensity beamline will boost radioactive isotope production by a factor of 10 to 50 and increase the scientific productivity many-fold, taking ISAC into a unique beam-power regime and ensuring its continued competitiveness for the coming decade and beyond.

In addition to these activities, TRIUMF plays a critical role in providing basic infrastructure to the Canadian subatomic physics community nation-wide. This role includes detector and electronics R&D, construction support for major elements of detectors used abroad by Canadian groups, and support for high-performance computing in Canada for major Canadian subatomic physics projects. Some of TRIUMF's highly trained staff of scientists, engineers, and technicians are supported at universities across the country, providing an invaluable resource for those universities and experiments in support of this infrastructure role.

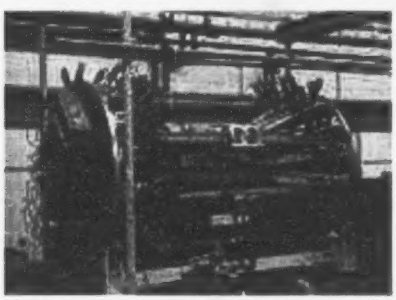
The BaBar drift chamber and the ATLAS hadronic endcap calorimeter are examples of significant detector components built at TRIUMF. TRIUMF has also been instrumental in providing support for the G0 experiment at JLab, and will continue this effort with the QWeak experiment at JLab. In each of these cases, TRIUMF's expertise and support enabled a significant Canadian contribution to the project.

TRIUMF will also host the ATLAS Tier-1 computing centre, providing critical support for the commissioning and calibration of the ATLAS detector and for data analysis. This role, supporting the leadership of Canadians in the competitive ATLAS physics analysis environment, was identified as a critical part of the TRIUMF program in the recent TRIUMF five year plan. TRIUMF also hosts a significant part of the Laboratory for Advanced Detector Design (LADD), funded by the CFI to renew the electronics and mechanical infrastructure necessary for the design of complex detector elements and their readout.

With a long history of accelerator design, TRIUMF accelerator and target scientists are in demand throughout the world. TRIUMF and its staff provide a vehicle by which Canada may make significant in-kind contributions to international accelerator projects, allowing Canadian access to these facilities. For the CERN Large Hadron Collider, TRIUMF staff designed and oversaw construction of magnets and provided components of the injection system upgrade. These important in-kind contributions to the LHC enabled Canadian scientists to join the ATLAS experiment. TRIUMF is also designing target handling systems to be used for the neutrino production targets at J-PARC in Japan, in support of strong Canadian participation in the T2K experiment. TRIUMF scientists are already taking part in some of the design challenges for the ILC; major Canadian participation in the ILC accelerator and/or possible LHC upgrades, led by TRIUMF, is a possibility in the future.

These infrastructure support roles of TRIUMF are of the highest importance and their budget implications are a particular concern to the community. While TRIUMF cannot apply directly to the CFI, new tasks undertaken in support of the subatomic physics community's vision often give rise to long-term operational commitments for TRIUMF; the repercussions for the laboratory must be understood and provided for in a way that does not detract from TRIUMF's on-site support of the ISAC program. In support of its mission, TRIUMF should be able to access all SAP-relevant funding agencies, including the CFI.

The subatomic physics community has some input to the development of the TRIUMF budget request through participation in TRIUMF planning exercises. However, the final level of funding and priorities for TRIUMF are decided as a part of the federal government's regular budget process, with little consultation. The LRP Committee would like to see a more transparent mechanism for the determination of TRIUMF's budget and a closer tie between that budget and the elements of TRIUMF's mandate and five-year plan. Here again, a mechanism such as the proposed MSIP, coupled with community driven long-range planning exercises, could help to ensure that the priorities of the community are taken fully into account.



The DAPHNE (Détecteur à grande acceptance pour la physique photonucléaire Expérimentale) detector at the Mainz Microtron in Germany, where Canadian physicists study photoproduction of nuclear resonances.

NSERC Major Facilities Access Grants

Technical support for detector and electronics development, experiment construction, accelerator design, and performance computing, is essential to the success of the subatomic physics program. If engineers, designers and technicians were supported purely on a project-by-project basis, their expertise would be lost between projects, making it difficult to maintain continuity and technical excellence. NSERC recognizes this, and provides common subatomic physics infrastructure support to universities through its Major Facilities Access (MFA) grant program. Subatomic physics MFAs differ somewhat from general MFAs; they do not need to be multi-institutional, provided they support multiple projects at a single institution. MFA awards are funded from within the GSC-19 envelope.

It is not possible to fund significant infrastructure at every university, and thus it is essential that those universities receiving MFA awards consider infrastructure support for subatomic physics researchers at other universities to be a part of their mandate. Multi-institution use of subatomic physics MFAs has not been uniform across the country. The LRP committee strongly recommends that the management of MFA-funded facilities be formalized, and that the availability of MFA personnel to support the entire subatomic physics community be widely communicated. We note that the MFA program is currently under revision, and will be replaced by the Major Resources Support (MRS) program. We encourage NSERC to consider the unique needs of subatomic physics while developing the MRS guidelines. A strong infrastructure program in Canada will be an efficient, cost-effective vehicle to help keep the entire Canadian subatomic physics community at the forefront of the field.

The SNOLab Facility

The International Facility for Underground Science (SNOLab) is an expansion of the current SNO site, and was funded through the CFI International Joint Ventures fund. By 2007 the construction of an additional large cavern and several smaller experimental halls will be complete, enabling several large astroparticle physics experiments to be located deep underground. SNOLab will be the deepest and cleanest underground facility in the world. This is of great importance to experiments requiring ultra-low background radiation and shielding from cosmic rays.

A new surface complex with modern laboratories, office space, and clean-room facilities is already complete and in operation.

SNOLab will provide infrastructure by making space available and providing basic services to experiments in the challenging underground environment. SNOLab has highly trained technical staff and research scientists who have expertise in performing underground experiments with low background materials. These personnel will provide technical, logistic and engineering support for the SNOLab experimental program.

The Institute of Particle Physics

The Institute of Particle Physics (IPP) employs eight research scientists based at Universities across the country. These researchers hold positions that mirror those of faculty at Canadian universities, with the difference that NSERC/IPP funding relieves them of teaching duties and allows them to lead Canadian particle physics projects on a full time basis. They are therefore able to spend significant amounts of time at the off-campus laboratories where particle physics experiments are carried out. IPP research scientists have held positions as spokespersons, physics coordinators, and run coordinators in experiments around the world. Although they are associated with a single Canadian institution, they often act as a liaison for the entire Canadian community working at a foreign laboratory.

A Theory Institute?

There is a widespread consensus that the Canadian subatomic physics theory community would benefit from an institute that would organize workshops, schools and summer programs. However, at the current time there is no consensus in the theory community for a bricks-and-mortar institute where research funds would be used to support administrative and computing infrastructure in addition to research activities.

Workshops and topical schools are an important mechanism in the education of subatomic physics researchers, allowing the widely-distributed Canadian community to benefit from its broad range of expertise. Hosting international conferences and workshops helps raise the Canadian community's profile, and is an important responsibility of international scientific citizenship that we currently cannot fully meet. Finding funds for the organizational costs of schools, workshops, and meetings is difficult; NSERC does not provide such support.

Theorists hard at work at the Perimeter Institute in Waterloo, Ontario.

A tape robot used to access the data from Fermilab's collider experiments.

There is consensus that existing institutes such as the Perimeter Institute and TRIUMF could and should provide the necessary administrative support and physical infrastructure to hold schools, workshops, and summer programs. These institutes do in fact run such programs – for example, the TRIUMF Summer Institute is now in its 18th year. However, there is no transparent procedure for submitting and selecting proposals for meetings. The ad hoc Theory long-range planning committee suggested that a governing council made up of Canadian theorists be formed to consider such proposals. Successful proposals would be organized and conducted by the proposing individuals taking advantage of the existing infrastructure, including administrative support, at TRIUMF or the Perimeter Institute.

It would also benefit the community if well advertised summer visitor programs, based on specific themes, were initiated at the Perimeter Institute and TRIUMF. For such programs to succeed and earn the support of the theory community, they must be widely advertised, the procedure for deciding on topics and programs must be transparent, and they must be inclusive to the entire theory community.

Computing and Network Infrastructure and the ATLAS Computing Centre

Computers are essential in subatomic physics for data analysis, simulation of experiments, and sophisticated theory calculations. Experiments with very large and continuous data flows and analyses are best served by large dedicated facilities. Other applications can often be accommodated in shared infrastructure facilities.

The largest experiments such as those at the LHC will generate petabytes (1 PB = 10^6 GB) of raw data each year [4]. Typically this will be archived and initially reconstructed at the experimental site. It will also be sent to remote sites where it is further analysed and, when better calibration constants are available, reprocessed to optimize the information available from the raw data. These activities require a continuous use of extensive resources, a usage pattern not suitable for a shared computing facility. The CFI Exceptional Opportunities Fund has recently funded a dedicated Tier 1 data centre, to be situated at TRIUMF, for the ATLAS experiment. It is reasonable to expect that the

[4] Storage for each experiment at the LHC for one year's data would require a stack of conventional DVDs as high as the CN Tower!

International Linear Collider will require a similar facility towards the end of the 10-year window of this report.

Large projects involve a variety of activities that are suitable for shared computing facilities, including analysis efforts by individual physicists, and production of simulated data. Projects in Canada with smaller computing requirements also make extensive use of such facilities. Examples include the TWIST experiment at TRIUMF and the BaBar experiment, which have used CFI-funded computing centres such as WestGrid and another in Victoria for a large part of their computing requirements. These activities have been enabled by extensive CFI investments combined with provincial support. We strongly support the renewal and expansion of these shared facilities, which will form the backbone of subatomic physics computing apart from the dedicated ATLAS "Tier 1" centre. This expansion is currently the focus of the CFI National Platforms Fund initiative. The needs of the theory community are generally met by these shared centres, although there is a dedicated 260-processor lattice QCD farm at the University of Regina.

Computing facilities alone do not provide effective infrastructure unless there is an effort to develop efficient tools for their exploitation and a national program to coordinate their use. In the Canadian subatomic physics community, the development of standardized tools for effective use of the Grid is an important ongoing effort, and the NSERC-funded HEPNET consortium coordinates networking in Canada and abroad. The subatomic physics community in Canada strongly supports continued NSERC funding for network infrastructure needed for our field but not funded by other agencies.

Canadian subatomic researchers also make extensive use of the CANARIE network infrastructure. CANARIE provides a backbone of dedicated high speed links between universities and research institutions in Canada. ATLAS Canada, in particular, will rely heavily on this infrastructure as it develops the centres and toolkits to be used for Grid computing. This networking infrastructure is essential to collaborative university based research and must be maintained.

Summary

The expertise in accelerator, beam-line, and detector development and construction that is accumulated in TRIUMF, SNOLab and in universities across the country is an invaluable asset for Canadian subatomic physics. This infrastructure also has a positive impact in a broader Canadian context. That impact is difficult to quantify, but is felt in areas such as the production of radioactive isotopes for medical treatments, materials science measurements performed at the Canadian Light Source and at TRIUMF, and the training of highly qualified personnel that leave the field for Canadian high-tech companies.

The funding situation for SAP is complex due to the variety of agencies and infrastructure resources which support the community, and could be balanced and streamlined. In addition, the GSC-19 funding envelope must increase to keep pace with the growth in the field and the operation of new infrastructure facilities. Finally, we support the establishment of a coherent oversight process for the different, but related, funding mechanisms and infrastructure facilities.

7 Funding Scenarios & Discussion

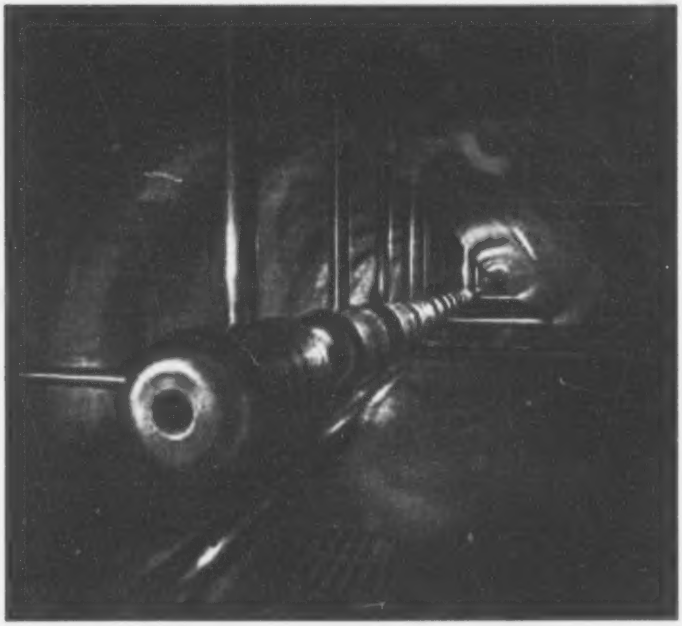
The scientific vision of the Canadian Subatomic Physics research community over the next five to ten years is detailed in the reports received by the Long-Range Planning Committee (LRPC) from the Division of Nuclear Physics (DNP), the Institute of Particle Physics (IPP), SNOLab Underground Astroparticle Physics, Theory, and Computing communities. These reports are listed in Section 9.2. The charge to the LRPC (reproduced in full in Section 9.1) was to make recommendations regarding the implementation of this scientific vision, including both how to best support the present program and how to incorporate new initiatives arising from a growing community, within the financial constraints of three funding scenarios:

i) Significantly more funding available to the discipline, consistent with a doubling of the GSC-19 envelope budget over the ten-year period of the plan,
ii) Status Quo funding, and
iii) Significantly less funding available to the discipline, consistent with a 20% cut to the GSC-19 envelope over the ten years of the plan.

Following extensive input from the community, the LRPC's deliberations regarding each of these funding scenarios led to the budgetary recommendations presented here.

7.1 Structure of the Budget Tables

A central aspect of long-range planning for the subatomic physics community is an understanding of the fluctuating balance between operating funds and capital investments in major equipment. To provide guidance to the NSERC GSC, the LRPC has made forecasts of all currently committed, as well as known forthcoming, capital projects as described in the reports received from the sub-communities and in NSERC documents. Each budget table presented in Section 7.2 contains a year-by-year breakdown of the capital currently committed from the envelope, including commitments made by the GSC in the 2006 competition. For this purpose, the high-priority projects are used to label the current capital commitments, which total \$10.3M over the first five years of the plan (2006–2010). In these capital commitments, ATLAS includes the "cost-to-completion", ISAC is primarily the TIGRESS and EMMA spectrometers, and "Breadth" is the contributions to the Qweak experiment and the $\pi \rightarrow e\nu$ experiment at TRIUMF.



Drift tubes inside a linear accelerator at Fermilab. The beam is accelerated down the central axis of the structures.

Control room of the new ISAC-II facility at TRIUMF, where beams of radioactive ions are directed to the experimental facilities.

In addition, new capital initiatives over these first five years are projected on a yearly basis using these same headings, with the addition of capital investments in SNOLab experiments beginning in 2007 in most funding scenarios. For ATLAS, new capital initiatives might include increasing the processing power of the high-level trigger system and/or potential upgrades to the detectors and readout systems. ISAC-related requests are likely for upgrades to the 8π spectrometer as well as smaller amounts for other instruments, and are detailed in the nuclear physics brief to the LRPC. The SNOLab community has identified capital requests for underground experiments (DEAP, EXO, Majorana, PICASSO, SNO+, ...) totaling over $20M in its report to the LRPC. The prioritization of these experiments, and recommendations regarding which should proceed to full implementation at SNOLab, is the mandate of the SNOLab Experiment Advisory Committee (EAC) and the LRPC does not presume to prejudge their conclusions here. The T2K long-baseline neutrino oscillation experiment is expected to submit a request for detector electronics in the 2007 competition, and possibly a request for further detector contributions beginning in 2009. Finally, the new capital initiatives listed under the "Breadth" heading will ensure the maintenance of a healthy diversity of research interests in Canadian subatomic physics and may include, but is by no means limited to, capital investments in experiments at the JLab 12-GeV upgrade, rare decays, high-energy astroparticle physics, and anti-hydrogen research.

We stress that in the "New Capital Initiatives" section of the budget tables, we are not explicitly endorsing the details of any of these anticipated requests; it would be premature for us to do so without full technical details of the costs and physics impact of each proposal. We recognize, however, that these categories represent the major initiatives of the Canadian subatomic physics community,

that there is substantial human and capital investment and substantial scientific merit in each of them, and that their continued development and operation will certainly bring to light new opportunities and new visions that the community will want to pursue. While the exact division of capital resources among these forthcoming initiatives must be determined by the GSC based on the detailed evaluation of the funding requests, the year-by-year breakdown presented in the budget tables illustrates how funding of these new initiatives over the next five years will need to be profiled, together with the current capital commitments, to satisfy the constraints of each funding scenario.

For the second five years of the plan (2011–2015), the budget tables present sums for the period that will, of course, need to be revisited and expanded upon by a future LRP exercise. In this period, significant Canadian participation in the International Linear Collider (ILC) is added to the high priorities ATLAS, ISAC, SNOLab, T2K, and Breadth of the program, all of which are expected to continue.

In that period, the direction of the Canadian community working at the energy frontier will be strongly influenced by future international decisions regarding timelines for the development of the ILC and/or a potential upgrade to the LHC. This reality is explicitly indicated in the tables by joining the ATLAS and ILC lines during this period. While approximate, the sums in the budget tables for the 2010-2015 period do provide long-term guidance regarding forthcoming capital requirements beyond the first five years of the plan and, as will be discussed in Section 7.2, also clearly demonstrate the impact each of the funding scenarios would have on the achievement of the long-term scientific vision of the Canadian subatomic physics community.

In addition to the capital projections, the budget tables in Section 7.2 contain recommendations for Experimental Operations, Theory, MFA/Infrastructure, and R&D/Instrumentation for each of the funding scenarios. The Experimental Operations are the sum of all Project, Group, and Individual grants of subatomic physics experimentalists and represent the largest budgetary item. While a breakdown of these funds among the major projects was examined by the LRPC under various funding scenarios as a "proof-of-principle" for the recommended totals, the exact subtotals depend strongly on the presumed timelines for the flow of researchers among the projects and the research disciplines of new applicants, neither of which can be predicted accurately. The LRPC therefore chose to present the total Experimental Operations which, in its opinion, would be an appropriate balance between capital and operations expenditures in the various funding scenarios. The allocation to individual projects based on the usual criteria of excellence and need is, of course, the purview of the GSC.

The Theory operations line is comprised almost exclusively of Individual Discovery Grants, while the MFA/ Infrastructure line includes the Major Facilities Access

(MFA) grants supporting subatomic physics infrastructure at Canadian universities, as well as the IPP grant. Finally, the R&D/Instrumentation line represents research efforts directed toward the development of new instrumentation and research directions, such as R&D for several potential SNOLab experiments, for the proposed GLUEX experiment at JLab, for the ILC, and for general instrumentation developments. While it is understood that not all projects supported in this category will become full experiments, the exploration of new technologies is essential to the future vitality of subatomic physics and was therefore considered as a separate item by the LRPC.

As with the capital projections, year-by-year breakdowns of the operating funds are provided for the first five years of the plan, and a sum over the second five years is given. The historical data from the 2005 competition are also provided for reference. To these total capital and operating expenditures are added repayments from the envelope associated with the Special Research Opportunities (SRO) program and the ATLAS cost-to-completion loan to obtain fiscal year totals, and year-by-year and cumulative surplus/deficits for the envelope under each funding scenario.

The Canadian subatomic physics community has grown rapidly in the last five years, and the number of subatomic physics graduate students in Canada has increased by approximately 55% during that time (see Figure 4 in Section 5.2). We expect this trend to continue for the next five years, as new faculty hires ramp-up their research programs and recruit additional students to their groups. As a figure of merit for the level of operating support in the various budget scenarios, the LRPC has used the ratio of the total GSC-19 operating grants to the total number of Canadian subatomic physics graduate students. This ratio is then normalized to a value of 1.0 at the beginning of the previous 5-year plan in 2001. Figure 5 shows the evolution of this ratio over the last five years, where it can be seen that the $\sim$ 55% increase in graduate student numbers has not been matched by corresponding increases in the GSC-19 envelope, leading to a steady decrease in operating funds per highly qualified person trained. We have projected this ratio for the next five years in each of the scenarios we considered, using the funding recommendations in the budget tables and the assumption that graduate student numbers in subatomic physics will continue to increase linearly over the next five years at the current rate. In fact, fully 25% of the subatomic physics research community in Canada has been hired within the last five years. Their research groups have only just begun to grow, and we might expect even stronger growth in the numbers of students during the coming five years.

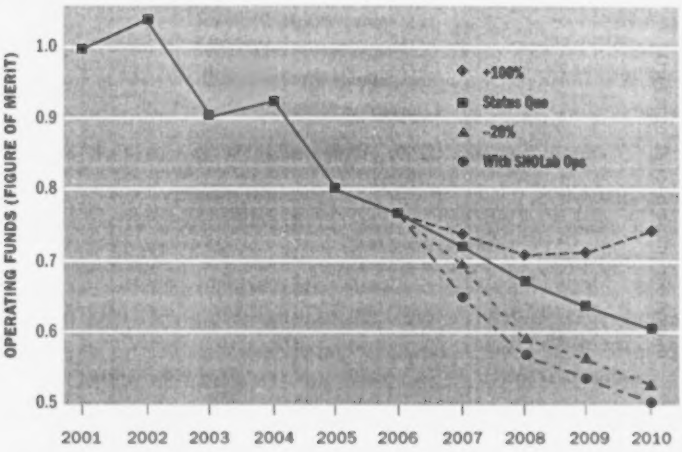


Figure 5: The operating funds figure of merit for the four funding scenarios considered by the LRPC.

The figure of merit is defined as the ratio of the total operating grants from GSC-19 to the total number of subatomic physics graduate students in Canada, normalized to a value of 1.0 in 2001. Graduate student numbers are projected to increase linearly over the next five years at the same average rate of growth as in the past five years (see Figure 4). Status quo funding for the GSC-19 envelope would therefore continue the steady decline in operating funds per highly qualified person trained that has been experienced in recent years.

The budget projections of Section 7.2 refer only to the NSERC subatomic physics envelope, and the LRPC made a number of assumptions regarding funding sources outside the envelope. These include the assumptions that TRIUMF will continue to be funded at or above its current level, that funding for large subatomic physics computing facilities will continue to be derived from non-envelope sources, that CANARIE funding will continue at or above its current level, and that operating expenditures for the new SNOLab facility will be found outside of the GSC-19 envelope. This final assumption is particularly urgent and is addressed explicitly by the LRPC in Section 7.3.

A module of the ATLAS Forward Electromagnetic Calorimeter, built at Carleton University, prior to delivery and installation at CERN.

7.2 Funding Scenarios

+100% Scenario

Table 1: Canadian Subatomic Physics Long-Range Planning Committee +100% Budget (in $M).

Year	05/06	06/07	07/08	08/09	09/10	10/11	Σ 06-10	Σ 11-15
Committed Capital								
ATLAS		0.6	0.6	0.0	0.0	0.0	1.3	0.0
ISAC		1.9	2.2	1.6	0.5	0.5	6.8	0.0
T2K		0.6	0.9	0.6	0.0	0.0	2.0	0.0
Breadth		0.2	0.0	0.0	0.0	0.0	0.2	0.0
Subtotal		**3.4**	**3.7**	**2.2**	**0.5**	**0.5**	**10.3**	**0.0**
New Capital Initiatives								
ATLAS				0.2	0.2	0.4	0.8	18.0
ILC								
ISAC					0.8	0.8	1.6	8.0
SNOLab			1.5	3.5	4.0	3.7	12.7	10.0
T2K			0.3	0.5	0.6	0.6	2.0	8.5
Breadth			0.2	0.1	0.8	1.2	2.3	7.5
Subtotal			**2.0**	**4.2**	**6.4**	**6.7**	**19.3**	**52.0**
Capital Total	**4.1**	**3.4**	**5.8**	**6.4**	**6.9**	**7.2**	**29.6**	**52.0**
Experimental Operations	**13.0**	**13.3**	**13.6**	**13.7**	**14.9**	**16.8**	**72.3**	**102.6**
Theory	**3.0**	**3.2**	**3.3**	**3.4**	**3.5**	**3.7**	**17.1**	**25.2**
MFA/Infrastructure	**1.8**	**1.9**	**2.0**	**2.1**	**2.2**	**2.3**	**10.3**	**14.1**
R&D/Instrumentation	**0.6**	**0.5**	**0.6**	**0.6**	**0.8**	**0.8**	**3.1**	**3.7**
Expenditures	**22.6**	**22.2**	**25.2**	**26.2**	**28.2**	**30.7**	**132.4**	**197.5**
Repayments	-0.6	0.1	-0.1	0.3	0.3	0.3	0.9	0.0
TOTAL	**21.9**	**22.3**	**25.1**	**26.5**	**28.5**	**31.0**	**133.3**	**197.5**
Envelope	22.2	22.5	24.4	26.4	28.6	31.0	132.9	197.5
Surplus/Deficit	0.3	0.3	-0.7	-0.1	0.1	0.0	-0.4	0.0
Cumulative Surplus/Deficit	0.4	0.7	0.0	-0.1	0.0	0.0	0.0	0.0

In the +100% funding scenario, the GSC-19 envelope is assumed to double from its 2006 competition value of $22.5M by the 2015 competition, corresponding to an 8.25% increase per annum. The budgetary recommendations of the LRPC under these funding conditions are presented in Table 1.

As shown in this table, modest increases in all of the Experimental Operations, Theory support, MFA/Infrastructure, and R&D/Instrumentation categories, are recommended by the LRPC. These increases in operating funds would ensure the level of support and number of HQP required to fully exploit the scientific potential of the major capital investments that have been made in the flagship programs of the Canadian subatomic physics community over the past decade, as well as maintain a healthy diversity of research interests in the discipline.

This funding scenario also allows the capital investments required to achieve a significant fraction of our scientific vision for the Canadian subatomic physics community as outlined earlier in this document. As indicated in Table 1, capital for ATLAS high-level trigger or detector upgrades would be available within the first five years of the plan, and sufficient capital could be devoted to the scientific programs at both an upgraded LHC and the ILC to ensure a leadership role for Canadian scientists. Similarly, capital for forthcoming ISAC detector upgrades would be available within the first five years of the plan, and major new detector investments to maintain ISAC's standing as the world-leading radioactive ion beam facility throughout the 2010–2015 period would be possible. Major capital investments for SNOLab experiments could be made in each of the five year periods, beginning as early as 2007 and potentially totaling more than $20M over the duration of the plan. This level of investment, concentrated in a small number of scientifically compelling experiments, would allow Canadians to remain world leaders in underground astroparticle physics. The +100% funding scenario would provide capital for T2K electronics as well as for additional contributions in the first five years of the plan and, in the second five years, would allow the Canadian community to play a major role in a subsequent long-baseline neutrino oscillation experiment informed by the T2K results. It would also permit capital investments in the first five years of the plan to maintain and stimulate the current diversity of the community and, in the second five years, allow significant capital investments in entirely new research initiatives that are certain to be brought forward by the new scientists joining the Canadian subatomic physics community.

In summary, the +100% funding scenario would allow the Canadian subatomic physics community to achieve the scientific vision described in Section 3. The LRPC stresses, however, that it is only this scenario that permits this level of achievement. Over the past decade, Canada has made major capital investments in flagship subatomic physics facilities such as ATLAS/LHC (~ $70M), ISAC (~ $115M), and SNOLab (~ $45M). It will only be through a corresponding increase in the NSERC GSC-19 envelope, at or above the sustained 8.25% per annum scenario explored here, that the community will be positioned to reap the full scientific potential of these investments.

Status Quo Scenario

In the status quo funding scenario, the $22.5M envelope for the 2006 GSC-19 competition is expected to increase to approximately $22.8M for the 2007 competition as a result of the final adjustment from the 2002 Reallocation exercise and a modest increase for new applicants. For the 2008 competition a further modest increase to $23.0M for new applicants is assumed, and the LRPC has then adopted the conservative perspective of a flat $23.0M envelope for the remainder of the plan with no further increases for either inflation or new applicants.

The budgetary recommendations for this scenario are presented in Table 2. Under these conditions the LRPC recommends flatlining all of the Experimental Operations, Theory, MFA/Infrastructure, and R&D/ Instrumentation categories at approximately their current absolute dollar values. It must be stressed that this would represent a real decrease in operating funds over the course of the 10-year plan, due both to inflation and to the expected increase in size of the

community. Such decreasing operating support for a growing number of researchers would harm the community's ability to exploit the scientific potential of the past decade's major capital investments and would become the limiting factor in the number of HQP that could be trained. This curtailing of operating funds would be the only means by which sufficient capital investments could be made to realize key aspects of the community's long-term scientific vision. Even with these restrictions on operating funding, the status quo funding scenario would require serious descoping of this vision.

As indicated in Table 2, reduced capital would be available for ATLAS upgrades within the first five years of the plan. The capital available in the second five years of the plan would be sufficient to allow a significant Canadian role in the science program at only one of the ILC or an upgraded LHC, and the capital funds available for detector contributions at such a future energy-frontier

Table 2: Canadian Subatomic Physics Long-Range Planning Committee Status Quo Budget (in $M).

Year	05/06	06/07	07/08	08/09	09/10	10/11	Σ 06-10	Σ 11-15
Committed Capital								
ATLAS		0.6	0.6	0.0	0.0	0.0	1.3	0.0
ISAC		1.9	2.2	1.6	0.5	0.5	6.8	0.0
T2K		0.6	0.9	0.6	0.0	0.0	2.0	0.0
Breadth		0.2	0.0	0.0	0.0	0.0	0.2	0.0
Subtotal		**3.4**	**3.7**	**2.2**	**0.5**	**0.5**	**10.3**	**0.0**
New Capital Initiatives								
ATLAS					0.1	0.2	0.3	} 10.0
ILC								
ISAC					0.5	0.5	1.0	4.0
SNOLab			0.5	2.0	2.0	2.5	7.0	5.0
T2K			0.3	0.5	0.2	0.0	1.0	0.0
Breadth			0.1	0.0	0.3	0.3	0.7	1.8
Subtotal			**0.9**	**2.5**	**3.1**	**3.5**	**10.0**	**20.8**
Capital Total	**4.1**	**3.4**	**4.6**	**4.6**	**3.6**	**4.0**	**20.3**	**20.8**
Experimental Operations	**13.0**	**13.3**	**13.3**	**13.3**	**13.3**	**13.3**	**66.5**	**66.5**
Theory	**3.0**	**3.2**	**3.2**	**3.2**	**3.3**	**3.3**	**16.2**	**16.5**
MFA/Infrastructure	**1.8**	**1.9**	**1.9**	**1.9**	**1.9**	**1.9**	**9.4**	**9.7**
R&D/Instrumentation	**0.6**	**0.5**	**0.2**	**0.3**	**0.3**	**0.3**	**1.5**	**1.5**
Expenditures	**22.6**	**22.2**	**23.2**	**23.3**	**22.4**	**22.8**	**113.9**	**115.0**
Repayments	-0.6	0.1	-0.1	0.3	0.3	0.3	0.9	0.0
TOTAL	**21.9**	**22.3**	**23.1**	**23.6**	**22.7**	**23.1**	**114.8**	**115.0**
Envelope	22.2	22.5	22.8	23.0	23.0	23.0	114.3	115.0
Surplus/Deficit	0.3	0.3	-0.4	-0.6	0.3	-0.1	-0.5	0.0
Cumulative Surplus/Deficit	0.4	0.7	0.3	-0.2	0.1	0.0	0.0	0.0

collider would still be below the standard set by past investments. The capital available for ISAC detector upgrades would be reduced in the first five years of the plan and, relative to Table 1, roughly halved in the second five years, jeopardizing the world-leadership of the ISAC science program. In the status quo scenario, the largest new capital investments in the first five years of the plan are associated with SNOLab experiments. Even so, the ramp-up of these investments would be delayed and the total funding would be sufficient for the Canadian community to play a leadership role in only one major SNOLab experiment. Electronics for the T2K experiment would remain a priority, but neither a further detector capital contribution within the first five years nor a major Canadian role in a follow-on long-baseline neutrino experiment in the second five years would be possible. A flat envelope would also significantly curtail the capital available to maintain the breadth of the community and drastically reduce the scope for new initiatives in the second five years of the plan.

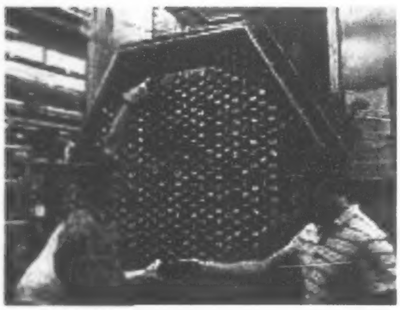
Flat funding for the GSC-19 envelope over a 10-year period is clearly a scenario that would both significantly limit the ability of the Canadian subatomic physics community to exploit the major capital investments of the past decade and jeopardize its ability to achieve the long-term scientific vision described in Section 3. The LRPC thus considers significantly increased envelope funding to be essential in order for the growing Canadian subatomic physics community to realize its full scientific potential.

Aerial view of TRIUMF, Canada's national laboratory for nuclear and particle physics research, in Vancouver, British Columbia.

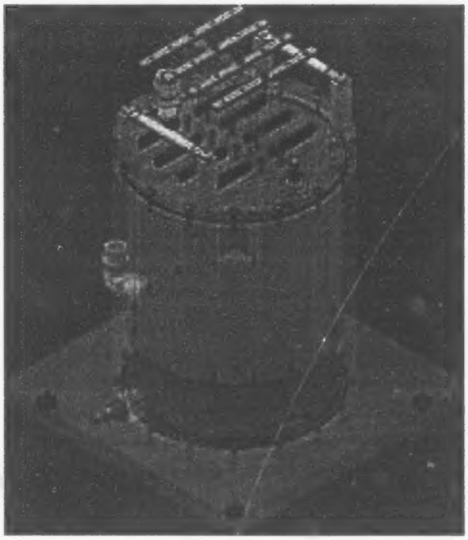
–20% Scenario

Table 3: Canadian Subatomic Physics Long-Range Planning Committee –20% Budget (in $M).

Year	05/06	06/07	07/08	08/09	09/10	10/11	Σ 06-10	Σ 11-15
Committed Capital								
ATLAS		0.6	0.6	0.0	0.0	0.0	1.3	0.0
ISAC		1.9	2.2	1.6	0.5	0.5	6.8	0.0
ISAC		1.9	2.2	1.6	0.5	0.5	6.8	0.0
T2K		0.6	0.9	0.6	0.0	0.0	2.0	0.0
Breadth		0.2	0.0	0.0	0.0	0.0	0.2	0.0
Subtotal		**3.4**	**3.7**	**2.2**	**0.5**	**0.5**	**10.3**	**0.0**
New Capital Initiatives								
ATLAS					0.1	0.2	0.3	6.0 (ATLAS + ILC)
ILC								
ISAC					0.5	0.5	1.0	3.5
SNOLab			0.5	2.0	2.0	2.5	7.0	4.5
T2K			0.3	0.5	0.2	0.0	1.0	0.0
Breadth			0.1	0.0	0.3	0.3	0.7	0.0
Subtotal			**0.9**	**2.5**	**3.1**	**3.5**	**10.0**	**14.0**
Capital Total	**4.1**	**3.4**	**4.6**	**4.6**	**3.6**	**4.0**	**20.3**	**14.0**
Experimental Operations	**13.0**	**13.3**	**13.0**	**11.4**	**11.4**	**11.4**	**60.5**	**56.0**
Theory	**3.0**	**3.2**	**3.1**	**3.1**	**3.1**	**3.1**	**15.6**	**15.5**
MFA/Infrastructure	**1.8**	**1.9**	**1.8**	**1.8**	**1.8**	**1.8**	**9.2**	**9.0**
R&D/Instrumentation	**0.6**	**0.5**	**0.2**	**0.2**	**0.2**	**0.2**	**1.3**	**0.0**
Expenditures	**22.6**	**22.2**	**22.8**	**21.2**	**20.1**	**20.5**	**106.8**	**94.5**
Repayments	-0.6	0.1	-0.1	0.3	0.3	0.3	0.9	0.0
TOTAL	**21.9**	**22.3**	**22.7**	**21.5**	**20.4**	**20.8**	**107.7**	**94.5**
Envelope	22.2	22.5	22.0	21.4	20.9	20.4	107.2	94.5
Surplus/Deficit	0.3	0.3	-0.7	0.0	0.5	-0.5	-0.5	0.0
Cumulative Surplus/Deficit	0.4	0.7	0.0	0.0	0.4	0.0	0.0	0.0



Students working on the barium floride calorimeter of the Two-Arm Photon Spectrometer at the Mainz Microtron in Mainz, Germany.



Engineering drawing of a test cell used to evaluate micropattern gas detector readout systems for Time Projection Chambers (TPCs). TPCs are likely to be used at the heart of ILC detectors and are the subject of intense R&D.

In the –20% funding scenario, the $22.5M envelope for the 2006 GSC-19 competition is assumed to decrease at 2.45% per annum to reach 80% of its current value by the 2015 competition. The budgetary recommendations of the LRPC in this funding scenario are presented in Table 3. The conclusion of the LRPC was that if the community were faced with such a scenario, investments in capital during the first five years of the plan must be protected in order to preserve some future prospects for the discipline should the funding scenario improve in later years. The recommended capital investments within the first five years are thus unchanged relative to Table 2, and the severe cuts associated with this funding scenario during the first five years are therefore extracted entirely from operating funds. The largest fraction of these cuts would necessarily come from experimental operations, which would be reduced to a level that would both decrease the diversity of the community and compromise its ability to extract significant physics from the major investments of the past decade.

In the first five years of this –20% funding scenario, operations would be reduced to a level barely sufficient for a reduced set of experiments. The cuts associated with the continuation of this scenario for the full duration of the plan would therefore have to be extracted from planned capital investments during the second five years. As shown in Table 3, the limited capital available in the second five years would allow only minor participation in either an upgraded LHC or the ILC, would severely limit the capital investments in ISAC and SNOLab detectors, and would eliminate the diversity of the community and its ability to invest in R&D and new research directions.

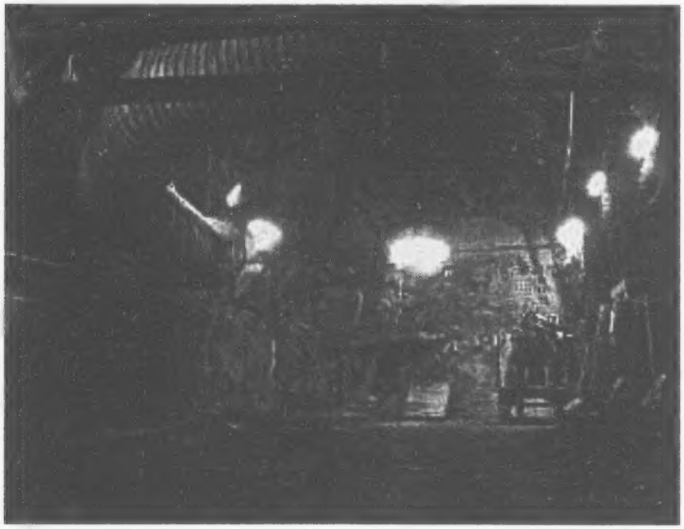
The –20% funding scenario would thus do serious damage to Canadian subatomic physics. In the near-term, we would lose the ability to rapidly and fully exploit the scientific potential of past investments, while in the long-term all diversity would be eliminated and the prospects for all of the community's high-priority programs would be severely curtailed.

7.3 SNOLab Operations

As noted in Section 7.1, all of the budgetary recommendations of Section 7.2 have been made under the assumption that the funding to operate SNOLab will be derived from sources outside of the GSC-19 envelope. Because the source of the operations funding for SNOLab has not yet been identified, the LRPC examined an additional funding scenario beyond those explicitly included in the charge to the committee, namely a status quo funding scenario in which SNOLab facility operations must be found from within the envelope. The other assumptions regarding the envelope remain the same as those described in Section 7.2.

The budget projections in this scenario are presented in Table 4. It can be seen that the negative consequences for Canadian subatomic physics would be immediate and severe. As SNOLab construction is completed over the next year and facility operations costs turn on, an immediate decrease in Experimental Operations to below the levels shown in Table 3 would be required. Such a decrease would reduce the number of students trained, seriously compromise the community's ability to extract physics results from all of ATLAS, ISAC, SNOLab, and T2K, and eliminate all diversity from the community. Recent increases in theory funding would be reversed, leading to the potential loss of leading theorists and an inability to recruit new talent. The MFA/Infrastructure investments would be cut, resulting in the loss of some University Infrastructure groups and a reduction in the number of IPP research scientists, and the community's ability to invest in R&D for new initiatives would be virtually eliminated.

Even with the above draconian cuts to operating funds, the requirement to fund SNOLab facility operations from within the envelope would necessitate the cancellation of all other planned new capital initiatives in the next five years apart from the SNOLab experiments themselves. The result would be no

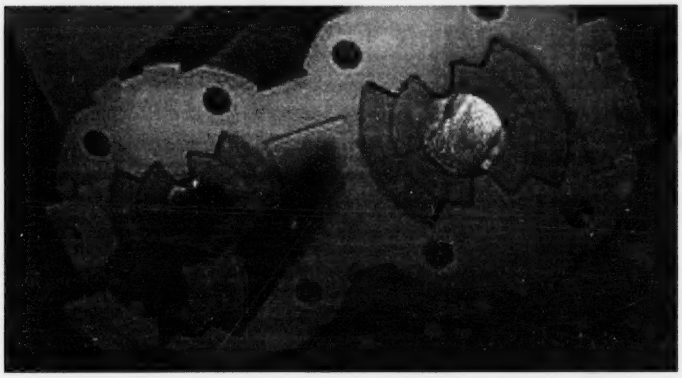


Excavation for the new SNOLab facility near Sudbury, Ontario, nearly 2 km underground.

capital for ATLAS or ISAC detector upgrades, no capital for T2K electronics, and the complete elimination of capital investments in all other parts of the community. Even with these cuts, the capital for SNOLab experiments would be delayed until at least 2008 and possibly 2009 and would be only a small fraction of what would be required for the Canadian community to be leaders in any major SNOLab experiment. In the second five years of the plan, Canada's participation in either the ILC or an upgraded LHC would be reduced to a peripheral role, and only minimal capital would be available for ISAC and SNOLab detector investments.

Table 4: Canadian Subatomic Physics Long-Range Planning Committee Status Quo Budget with SNOLab Facility Operations derived from inside the GSC-19 Envelope (in $M).

Year	05/06	06/07	07/08	08/09	09/10	10/11	Σ 06-10	Σ 11-15
Committed Capital								
ATLAS		0.6	0.6	0.0	0.0	0.0	1.3	0.0
ISAC		1.9	2.2	1.6	0.5	0.5	6.8	0.0
T2K		0.6	0.9	0.6	0.0	0.0	2.0	0.0
Breadth		0.2	0.0	0.0	0.0	0.0	0.2	0.0
Subtotal		3.4	3.7	2.2	0.5	0.5	10.3	0.0
New Capital Initiatives								
ATLAS							0.0	5.0
ILC							0.0	
ISAC							0.0	3.0
SNOLab			0.0	1.0	1.0	1.5	3.5	5.0
T2K							0.0	0.0
Breadth							0.0	0.0
Subtotal			**0.0**	**1.0**	**1.0**	**1.5**	**3.5**	**13.0**
Capital Total	**4.1**	**3.4**	**3.7**	**3.2**	**1.5**	**2.0**	**13.8**	**13.0**
Experimental Operations	**13.0**	**13.3**	**11.9**	**11.0**	**11.0**	**11.0**	**58.2**	**55.0**
Theory	**3.0**	**3.2**	**3.1**	**3.0**	**3.0**	**2.9**	**15.1**	**14.5**
MFA/Infrastructure	**1.8**	**1.9**	**1.7**	**1.6**	**1.5**	**1.5**	**8.1**	**7.5**
R&D/Instrumentation	**0.6**	**0.5**	**0.2**	**0.0**	**0.0**	**0.0**	**0.6**	**0.0**
SNOLab Facility Operations			**3.0**	**5.0**	**5.0**	**5.0**	**18.0**	**25.0**
Expenditures	**22.6**	**22.2**	**23.5**	**23.8**	**22.0**	**22.4**	**113.8**	**115.0**
Repayments	-0.6	0.1	-0.1	0.3	0.3	0.3	0.9	0.0
TOTAL	**21.9**	**22.3**	**23.5**	**24.1**	**22.3**	**22.7**	**114.7**	**115.0**
Envelope	22.2	22.5	22.8	23.0	23.0	23.0	114.3	115.0
Surplus/Deficit	0.3	0.3	-0.7	-1.1	0.8	0.3	-0.4	0.0
Cumulative Surplus/Deficit	0.4	0.7	0.0	-1.1	-0.3	0.0	0.0	0.0



The core of an LHC superconducting dipole magnet. The two chambers in which the two proton beams circulate are clearly visible.

The budget projections of Table 4 make it clear that operating funds for a major laboratory such as SNOLab are simply beyond the scope of the current GSC-19 envelope, and would reduce the Canadian community to mere operators of SNOLab, unable to participate meaningfully in experiments at our own facility. This scenario amounts to the complete devastation of the community's vision to retain its world-leading stature in key areas of subatomic physics research.

The LRPC notes that a clear distinction must be made between the operation of the current SNO experiment and the future operation of the SNOLab facility. The on-site operation of the current SNO experiment ($2.3M, $2.8M, $2.0M in 2005, 2006, and 2007, respectively) has been, and continues to be, supported from within the GSC-19 envelope. With the rapid decrease in SNO funding after 2007 as the experiment ceases operations, there is a temptation to assume that these funds could be redirected to partially offset the cost of operating SNOLab. This argument, however, neglects the community's long-term planning in which the ramp-down of operations for some experiments (in this case SNO) is concurrent with the need to ramp-up operations for other experiments. Furthermore, it neglects the fact that future experiments at SNOLab will also require onsite experimental operations funding similar to SNO's and beyond the basic services provided by the SNOLab facility. In order to avoid the crisis depicted in Table 4, it is essential that the full cost (estimated at approximately $5.0M/year) of operating SNOLab be secured from funding sources outside of the GSC-19 envelope.

8 Conclusion and Summary of Recommendations

The LRP Committee finds the Canadian subatomic physics community to be in very good health. Recent faculty renewal and strengthening, as well as major capital investments in recent years have allowed it to pursue its priority projects and have positioned it to play a central role in this exciting field over the next few years.

The vision for the community is clear. In the short-term, it is to exploit the world-leading facilities and experiments that we have helped to develop, and to participate as second-to-none partners in the exciting new physics to be done there.

Thus, the LRPC's first recommendation enunciates those priorities:

> **Scientific Recommendation:** The highest priority projects for the Canadian subatomic physics community over the next five years should be:

- optimal exploitation of the potential for new physics discoveries at the highest energies on earth using the ATLAS detector at the LHC at CERN;
- completion and optimal exploitation of the world's premier radioactive beam facility at ISAC (TRIUMF) and its state-of-the-art instrumentation for nuclear physics and nuclear astrophysics;

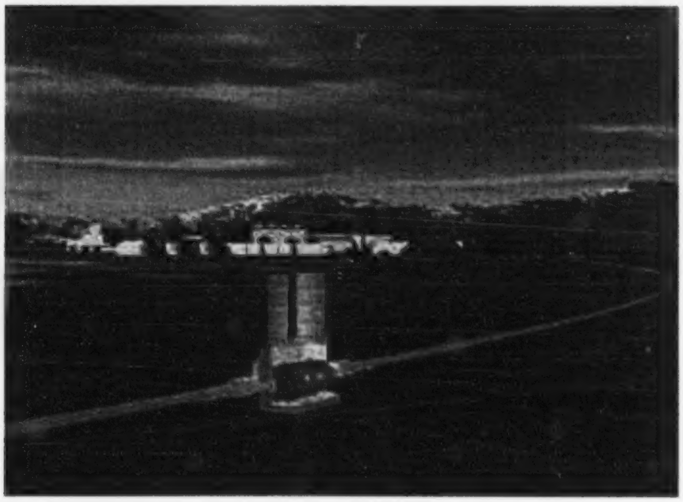
- completion of the SNOLab facility and development of it into the world's lowest-background laboratory, including participation in a suite of experiments to exploit this unique environment;
- construction and participation in the T2K neutrino experiment for investigations of the nature of neutrinos in a unique energy range.

On a longer timescale, the international community has identified the construction and operation of the International Linear Collider as the next major priority in particle physics, capable of fully exploiting the discoveries from the LHC era. Canada must be a strong player in this project, and the LRPC's second high-priority recommendation encapsulates that:

> **Scientific Recommendation:** The Canadian subatomic physics community should vigorously pursue R&D over the next several years to position ourselves for major involvement in the ILC in the second five years of this plan, and full participation in the international deliberations concerning the ILC's timing and location.

The LRPC views the current breadth of the community's activities, including its strong theory community, as an important asset that allows us to pursue new initiatives, affords us new opportunities for leadership, and gives our students a broader view of subatomic physics research. This forms our next recommendation:

> **Scientific Recommendation:** The Canadian subatomic physics community should participate in a diverse suite of smaller efforts to provide breadth to the community and to allow it to exploit new opportunities as they arise.



An artist's conception of an underground interaction region of the LHC at CERN.

The realization of this vision presents serious challenges to the community, its funding agencies, and its partners. In particular, major capital funds have been allocated in recent years without the concomitant operating funding being identified. This gives rise to our next two recommendations:

> **Funding Recommendation:** Immediate steps must be taken to identify new funds for the operations costs of the new CFI-funded SNOLab facility. With the SNOLab construction nearing completion, the need for these funds is urgent.

> **Funding Recommendation:** Because the status-quo and –20% scenarios for the NSERC subatomic physics envelope lead to unacceptable loss in the Canadian community's ability to exploit the recent major capital investments in our highest priority projects, substantial new funds must be allocated to the NSERC subatomic physics envelope, as envisaged in the +100% scenario.

Recent CFI capital funding in our field has been necessary and welcome, but has often occurred without regard to the ongoing operations funding necessary. This problem is not unique to our field, leading to our next recommendation:

> **Policy Recommendation:** A general mechanism should be developed to identify and allocate operations funding as new major capital investments are made.

The TRIUMF laboratory provides critical infrastructure to the entire Canadian subatomic physics community as well as operating the world's finest radioactive isotope accelerator complex. At the same time, most subatomic physics researchers in Canada are university-based and the local technical capabilities provided by the NSERC MFA/MRS program provide invaluable assistance in allowing them to assume positions of leadership in the field. Our final two recommendations recognize this double-pole of infrastructure support in the country:

> **Policy Recommendation:** The central role of the TRIUMF lab in providing infrastructure and support to subatomic physics in Canada must be nurtured and strengthened, and more transparency is needed in the budget process to coordinate with TRIUMF's mandate and five-year plan. In support of its mission, TRIUMF should be able to access all SAP-relevant funding agencies, including the CFI.

> **Policy Recommendation:** The NSERC MRS guidelines must be examined closely to ensure that subatomic-physics infrastructure will continue to be eligible for funding, and that infrastructure must be managed in a way that guarantees open access to the broad Canadian subatomic physics community.

Subatomic physics is entering an exciting era; truly revolutionary discoveries – new dimensions, dark matter, unified theories – may be exhilaratingly close. The Canadian subatomic physics community is well-positioned to play a leadership role in that era. We believe that implementation of the recommendations in this plan will allow us, five years hence, to be positioned at the very forefront of that revolution – recognized as leaders at home and actively sought out as scientific partners abroad – as we seek to continue the millenia-old quest to understand the very fundaments of the world around us.

9 Appendices

9.1 Long Range Plan: Charge, Procedures, and Committee

Long Range Plan for Subatomic Physics

Committee Composition:

The Committee will be made up of experts representing the main sub-groups supported by the Grant Selection Committee. These areas are Theory, Nuclear Physics (including nuclear astrophysics), High-Energy Physics, Neutrino Physics, and Particle Astrophysics. The Chair will be a senior Canadian having a broad overview of subatomic physics in Canada. It is expected that there will be some overlap in membership with the current GSC, and with the previous planning committee.

Mandate:

The Committee is to prepare a forward look for subatomic physics in Canada covering the period until 2016. This forward look will advise NSERC and the Subatomic Physics Grant Selection Committee (GSC) on the community's priorities for both current and future projects. It must be driven by the science of the community, and emphasize science goals.

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The plan must be prepared in consultation with the wider Canadian subatomic physics community, and with the groups which represent it. It is expected that the first five years (2006 to 2011) will be dealt with in somewhat more detail than the second five years (2011 to 2016). It is also expected that the plan will be revisited at the end of the first five year period.

The report should address three budget scenarios:

1 Status quo (that is, increases more or less consistent with inflation, but not above that);
2 Significantly more funding available to the discipline, consistent with a doubling of NSERC's budget over the ten-year period of the Plan;
3 Significantly less funding available to the discipline, consistent with a 20% cut to NSERC's budget over the ten years of the Plan.

Specific issues to be addressed by the Plan, in each of the scenarios outlined above, include:

- How best to support the present program, and
- How best to incorporate new initiatives into the program

The report must also take into account the following:

- The role of TRIUMF
- The role of theory
- The relationship between NSERC and other bodies which support subatomic physics in Canada (these include, but are not limited to, TRIUMF, NRC, the Canada Foundation for Innovation, and the universities)
- The fluctuating balance between investments in capital and operating funds within the NSERC subatomic physics envelope

The report should be addressed primarily to NSERC, but the committee is encouraged to address other parties as appropriate. The report will be a public document.

Process:

This is intended to be a community-driven process in which NSERC will act as an observer and resource. Input to the process will be solicited by the committee itself. Care must be taken to ensure that the process is open to participation by all members of the subatomic physics community.

The committee will be provided with financial support from NSERC for the purpose of organizing appropriate meetings, for the travel of committee members to these meetings, and for the preparation of the report.

The plan must be prepared in consultation with the wider Canadian subatomic physics community, and with the groups which represent it. It is expected that the first five years (2006 to 2011) will be dealt with in somewhat more detail than the second five years (2011 to 2016). It is also expected that the plan will be revisited at the end of the first five year period.

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Procedures

The LRP Committee met on August 12, 2005 in Ottawa to decide on a course of action for community input into the planning process. Shortly thereafter it invited comments and briefs about the long-term vision for subatomic physics from the community. Five briefs were received by November 2005, and are listed in Section 9.2.

A community-wide town hall meeting, attended by approximately 120 physicists from across Canada, was held at McGill University in Montreal on December 5-6, 2005. At this meeting the briefs were presented to the community and wide-ranging discussion followed.

The committee then met twice in person, on January 8-10, 2006 at TRIUMF, and on May 1-2, 2006 in Ottawa. In addition, frequent conference calls were held throughout the process.

Membership of the Committee

S. Bhadra York University
M. Butler St. Mary's University
J. Dilling TRIUMF
S. Godfrey Carleton University
C. Hearty University of British Columbia
G. Huber University of Regina
R. McPherson University of Victoria
T. Noble Queen's University
J.-M. Poutissou TRIUMF (ex-officio)
K.J. Ragan McGill University (chair)
D. Sinclair Carleton University (ex-officio)
C. Svensson University of Guelph
W. Trischuk University of Toronto (ex-officio)
K. Wilson CFI (ex-officio)

9.2 References

This report, and supporting background information, can be found at the web site **http://www.ap.smu.ca/lrp/**. Specific information mentioned in the report can also be accessed directly at the websites listed below.

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2. Input from the Institute of Particle Physics:
   http://www.ipp.ca/ipp_lrp2005.pdf

3. Input from the SNOLab community:
   http://www.ap.smu.ca/lrp/SNOLAB LRP Brief Final.pdf

4. Input from the theory community:
   http://www.ap.smu.ca/lrp/theoryplan.pdf

5. Brief on computing in Canadian Subatomic Physics:
   http://www.ap.smu.ca/lrp/computing_lrp-report.pdf

Other planning documents:

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   http://www.ap.smu.ca/lrp/doe.pdf
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4. Report from the US Committee on Biomedical Isotopes, Institute of Medicine, National Academy Press 1995.
5. B. Martin, et al., "The Relationship between Publicly Funded Basic Research and Economic Performance", Science Policy Research Unit, University of Sussex, U.K. (July, 1996).
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9.3 Glossary

ATLAS	An acronym for "A Toroidal LHC Apparatus"; one of two major detectors for the LHC.
CDF	The Collider Detector Facility, an experiment at the Tevatron accelerator at Fermilab.
CDMS	Cryogenic Dark Matter Search
CERN	The European Laboratory for Nuclear and Particle Physics (Geneva, Switzerland)
CFI	Canada Foundation for Innovation
CANARIE	Canada's Advanced Internet Development Organisation
CRC	Canada Research Chair
DEAP	Dark matter Experiment using Argon Pulse shapes
DRAGON	Detector of Recoils And Gammas Of Nuclear Reactions (at ISAC)
EMMA	ElectroMagnetic Mass Analyzer (at ISAC-II)
GSC	Grant Selection Committee (NSERC)
HERA	The Hadron Electron Ring Accelerator at DESY, Hamburg.
HQP	Highly Qualified Personnel
ILC	International Linear Collider
IPP	Institute of Particle Physics
ISAC	Isotope Separator and Accelerator Complex (at TRIUMF)
JLab	Thomas Jefferson National Accelerator Laboratory (Newport News, Virginia)
J-PARC	Japanese Proton Accelerator Research Complex (Tokai, Japan)
LEP	The Large Electron-Positron collider at CERN which ran from 1989 to 2000.
LHC	Large Hadron Collider (at CERN)
LRP	(SAP) Long-Range Plan

MFA/MRS	Major Facilities Access/Major Research Support programs (NSERC)
MSIP	Major Science Investment Panel
NRC	National Research Council
NSERC	Natural Sciences and Engineering Research Council
PET	Positron Emission Tomography
PICASSO	Project in Canada to Search for Supersymmetric Objects
QCD	Quantum Chromodynamics
SAP	Subatomic physics
SM	Standard Model
SNO	Sudbury Neutrino Observatory
SNOLab	A new laboratory at the site of the SNO experiment in the INCO Creighton Mine near Sudbury.
T2K	An acronym for Tokai-to-Kamiokande, a neutrino experiment in Japan.
TACTIC	TRIUMF Annular Chamber for Tracking and Identification of Charged Particles
TIGRESS	TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer
TITAN	TRIUMF Ion Trap for Atomic and Nuclear science
TRINAT	TRIUMF Neutral Atom Trap
Tevatron	The 2-TeV proton-antiproton collider at the Fermi National Accelerator Laboratory (Fermilab) near Chicago.
TRIUMF	The Tri-University Meson Facility on the UBC campus in Vancouver; TRIUMF is Canada's national particle and nuclear physics laboratory.
TUDA	TRIUMF-U.K. Detector Array
TWIST	TRIUMF Weak-Interaction Symmetry Test
VERITAS	Very Energetic Imaging Telescope Array System
WestGrid	Western Canada Research Grid
WIMP	Weakly Interacting Massive Particle
ZEUS	A detector at the HERA accelerator at DESY.

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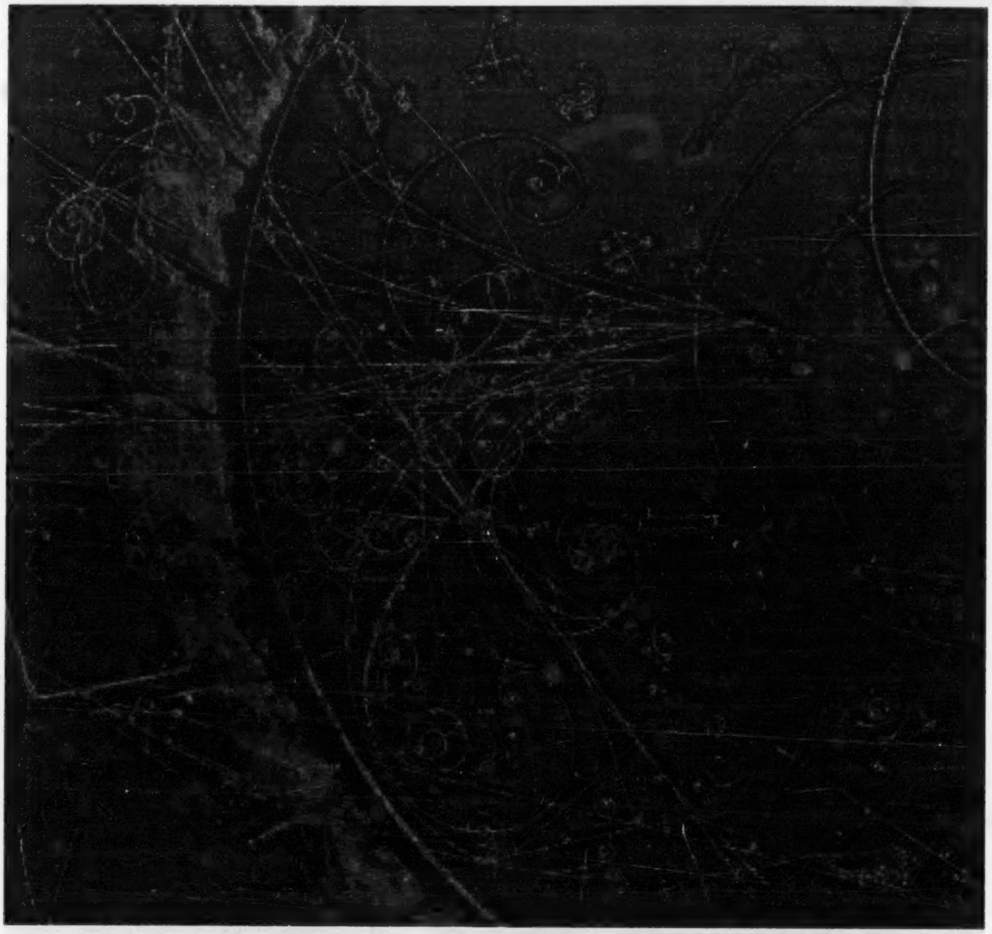

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